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Association Euratom - Risø National Laboratory for Sustainable Energy, Technical University of Denmark - Annual Progress Report 2009

Risø-R-Report

Edited by S.B. Korsholm, P.K. Michelsen, J.J. Rasmussen and C.M. Westergaard

Risø-R-1725(EN)
April 2010

Risø DTU
National Laboratory for Sustainable Energy

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Abstract (max. 2000 char.):

The programme of the Research Unit of the Fusion Association Euratom - Risø National Laboratory for Sustainable Energy, Technical University of Denmark, covers work in fusion plasma physics and in fusion technology. The fusion plasma physics research focuses on turbulence and transport, and its interaction with the plasma equilibrium and particles. The effort includes both first principles based modelling, and experimental observations of turbulence and of fast ion dynamics by collective Thomson scattering. Within fusion technology there are activities related to development of high temperature superconductors. Minor activities are system analysis, initiative to involve Danish industry in ITER contracts and public information. A summary is presented of the results obtained in the Research Unit during 2009.

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Preface

In 2006 seven parties, EU, Japan, Russia, China, USA, Korea and India, signed the agreement to build and exploit ITER, and to place ITER in Cadarache in France. ITER is a major experimental facility for the development of fusion as an energy source. It is expected that ITER will be ready for scientific exploitation in 2018. The mission of ITER is to demonstrate that nuclear fusion can be exploited as an energy source. ITER represents an unprecedented international cooperation in the field of science and technology. It also represents a valuable opportunity for cooperation between public research organisations and private industry. Risø DTU participates in the internationally coordinated activities to develop fusion and sees itself as having a key role in facilitating the participation of Danish industries in the international fusion programme.

The principle being pursued with ITER is the fusion of hydrogen isotopes to form helium. To make the fusion process run at a significant rate the hydrogen gas must be heated to high temperatures where it ionises and turns into a plasma. The plasma must be confined to achieve suitable densities and sustain the high temperature. ITER will use a magnetic field for the confinement. While fusion holds the promise of providing a sustainable source of energy, which is environmentally sound, it also presents considerable scientific and engineering challenges. Key issues in the final steps towards realising fusion energy production include:

Improving the plasma energy confinement, that is the ratio between the energy of the plasma and the heating power required to sustain the plasma energy. Improving energy confinement implies reducing energy transport out of the plasma, which principally is due to turbulence. Thus, one of the key issues is to understand and control turbulence.

Channelling the energy of fast ions, produced in fusion reactions, into heating the bulk plasma without driving turbulence and without premature exit of the fast ions from the plasma requires understanding and control of the dynamics of the fast ions in interaction with other particles and with waves.

After the merging with the Technical University of Denmark (DTU) in January 2007 Risø has become an institute under DTU with the new name Risø National Laboratory for Sustainable Energy, Technical University of Denmark, in short Risø DTU. As DTU covers many technical and scientific fields of interest for the development of fusion energy, the possibility for expanding the Danish activities in the field are being investigated. Investigations of advanced superconductors operating in high magnetic field are now included in the work plan 2010-2011. Other activities on neutron radiation damages and new material studies are under discussion.

The main contributions from Risø DTU to fusion research in 2009 have been: 1) Models for investigating turbulence and transport are continually improved, and benchmarked against experiments. 2) Central to understanding the dynamics of fast ions is temporally and spatially resolved measurements of the fast ion velocity distributions in the plasma. Risø DTU, in collaboration mainly with EURATOM partners, is exploiting and developing millimetre wave based collective Thomson scattering (CTS) diagnostics at the TEXTOR and ASDEX upgrade tokamaks in FZ-Jülich and the Max-Planck Institute for plasma physics in Garching (near Munich). Of particular note this year has been the demonstration of the feasibility for applying of CTS as a fuel ion ratio diagnostic.

1 Summary of Research Unit activities

The activities in the Research Unit cover the main areas:

Fusion Plasma Physics, which includes:

- *Theoretical and numerical turbulence studies*. Turbulence and the associated anomalous transport of particles, energy and momentum is investigated using first principles based models and solving these by means of numerical codes in full toroidal geometry. These models are continuously being developed and benchmarked against experimental data and codes at other associations. The activities mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas. The work is performed in collaboration with EFDA partners and in particularly with EFDA/JET.
- *Fast Ion Collective Thomson Scattering.* Risø has taken the lead in the development and exploitation of fast ion collective Thomson scattering diagnostics for TEXTOR, ASDEX Upgrade (AUG) and ITER. These projects are carried out in close collaborations with the TEC† and AUG teams.

Other activities in 2009 have been:

- Investigations of high temperature superconductors for fusion reactors with special emphasis on the characterization of various high temperature superconductor materials.
- Participation in the EFDA programme on developing a multi-region global long term energy modelling framework called EFDA-TIMES.
- Activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER.
- Activities on public information about fusion energy. This includes development and presentation of the "Danish Fusion and Plasma Road Show".

The **global indicators** for the Research Unit in 2009 are:

Professional staff:	13.6	man-years
Support staff:	3.0	man-years
Total expenditure - incl. mobility:	2.50	MioEuro
Total Euratom support:	0.61	MioEuro

† TEC: the Trilateral Euregio Cluster, a collaboration of FOM Institute for Plasma Physics, Holland; ERM/KMS, Belgium and Forschungszentrum Jülich, Germany.

2 Plasma Physics and Technology

2.1 Introduction

A plasma is a dense collection of free ions and electrons. The transitions from solids to fluids to gases are associated with increases in internal energy, the breaking of bonds and changes of physical properties. The same is true for the transition from a gas to a plasma. The plasma is rightfully described as the fourth state of matter, its physics differing as much from that of gases as that of solids does. As solid state physics is involved in a broad range of applications, it should be no surprise that plasmas have a wide range of applications, that their physics and chemistries are rich, and that the methods of generation and diagnosis are wide and complex.

Our activities in high temperature plasmas, aimed at developing fusion energy, are coordinated with the European EURATOM fusion programme through an agreement of association on equal footing with other fusion laboratories in Europe. Our EURATOM association facilitates extensive collaboration with other fusion research laboratories in Europe, crucial in the ongoing build-up of competencies at Risø DTU, and gives us access to placing our experimental equipment on large fusion facilities at the Max-Planck Institute for Plasma Physics in Garching and at the Research Centre Jülich, both in Germany. Our association with EURATOM also provides the basis for our participation in the exploitation of the European fusion research centre, JET, located in England. With its organisation of national programmes as EURATOM associations, the European fusion programme is a successful example of a large *European Research Area.* Our activities in high temperature plasma research and the development of fusion energy are introduced in subsection 2.1.1, and described in further detail in subsection 2.2 discussing turbulence and transport in fusion plasmas, and in subsection 2.3 discussing our use of millimetre waves for investigating the dynamics of fast ions in fusion plasmas.

2.1.1 Fusion plasma physics

http://fusion.risoe.dk

Producing significant amounts of fusion energy requires a plasma with a temperature of 100 to 200 million degrees and densities of 1 to 2 times 10^{20} particles per cubic metre, corresponding to a pressure of 1 to 5 atmosphere. Unlike gases, plasmas can be confined and compressed by magnetic fields. At the required temperatures the plasma must be lifted off material walls to prevent the plasma from rapid cooling. This is done by suspending the plasma in a toroidally shaped magnetic field that also acts to balance the plasma pressure. The required temperature and densities have been achieved in the joint European fusion experiment, JET. The production of net energy adds the requirement that the energy in the plasma be confined at least on the order of six seconds. The confinement time is the characteristic time for cooling off if heating was switched off or, equivalently, the ratio of plasma energy to required heating power to sustain that energy content. Achieved confinement times are on the order of one second. Higher density could compensate shorter confinement time and vice versa, so a simplified statement of the target is that the product of temperature, density and confinement time should be six atmosphere × seconds and is currently one atmosphere × seconds. Progress towards the goal principally involves improving the confinement time or, equivalently, reducing the energy transport in the plasma. The energy transport in fusion grade plasmas is principally due to turbulence, one of our main research activities reported in subsection 2.2. Significant progress towards the goal is expected with the next step fusion experiment, ITER. In ITER significant fusion rates are expected and with that the fast ion populations in the plasma will increase dramatically compared with present machines. The fast ions may then influence the plasma significantly. As a consequence, the dynamics of fast ions and their interaction with the rest of the plasma is one of the central physics issues to be studied in ITER. This is another of our main research topics in fusion as reported in subsection 2.3.

The fields of turbulence transport and fast ions are closely knit. With steep gradients in plasma equilibrium parameters and with populations of energetic ions far from thermal equilibrium, fusion plasmas have considerable free energy. This energy drives turbulence, which in turn acts back on the equilibrium profiles and on the dynamics of the fast ions. The turbulence naturally gives rise to enhanced transport, but also sets up zonal flows that tear the turbulent structures apart and result in transport barriers. The edge transport barrier being most likely at the root of the poorly understood, but experimentally reliably achieved, high confinement mode (H-mode). This non-linear interplay between turbulence and equilibrium also supports transient events reminiscent of edge localised modes (ELMs) where energy and particles are ejected from the plasma edge in intermittent bursts.

This set of topics is the focus of our fusion plasma physics research: With first-principles based codes we seek to model the interplay between plasma turbulence, transport and equilibrium. This modelling is tested against experimental data in collaboration with other fusion plasma physics institutes. To elucidate the physics of fast ions and their interplay with turbulence, waves and transient events, we are engaged in the diagnosis of confined fast ions by collective Thomson scattering (CTS) at the TEXTOR tokamak at the Research Centre Jülich and at the ASDEX upgrade tokamak in the Max-Planck Institute for Plasma Physics in Garching, both in Germany.

2.2 Turbulence and transport in fusion plasmas

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The transport of heat, particles, and momentum across the confining magnetic field of fusion plasmas is one of the most important, but also most difficult areas of contemporary fusion research. It is well established that the “anomalous” transport component due to low frequency turbulence is usually far larger than the classical and neo-classical collisional transport, in particular in the edge region. Therefore, it is of highest priority to achieve a detailed understanding of anomalous transport and the underlying turbulence for the design of an economical viable fusion reactor based on magnetic confinement schemes. In spite of the dramatic progress in experiment, theory and computations during recent years, the quantitative understanding is still sparse and lacking predictive capability. Even fundamental phenomena such as transitions from low confinement regime (L-mode) to high confinement regime (H-mode), the profile resilience and the particle pinch that are routinely observed and classified experimentally have no generally accepted explanations.

The activities within plasma turbulence and transport are mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas, but also investigations of core turbulence and transport are taken up. Generally, it is acknowledged that the conditions near the edge of the plasma are dictating the global performance, which seems natural since all transport has to go through the edge region, but certainly the coupling to the core plasma dynamics is essential. Theoretical and numerical investigations of first principle models form the majority of the work performed. We emphasize benchmarking of results and performance, both with other codes and analytic results (verification) and then also with experimental observations (validation).

Our activities are fully integrated into the EURATOM fusion program, and we have active collaborations with several EURATOM laboratories on theoretical issues as well as on direct comparisons of our results with experimental observations. We are strongly involved in the EFDA-JET program; V. Naulin is task force co-leader of Task-Force Transport. We are actively participating in the Integrated Tokamak Modeling (ITM) Task Force on validation and benchmarking of codes as well as defining the ITM data structures. From 2010 Anders H. Nielsen is deputy leader for project IMP4. Furthermore, we have a significant involvement in the EFDA Topical Groups, and have obtained several task agreements particularly within the TG Transport and TG MHD, see Sec. 2.2.1.

Several of our numerical codes are in use at different European laboratories, where they are employed for specific purposes, ranging from experimental comparisons to education of students. In that connection we have organized the 2nd ESEL workshop in November bringing together the key users of the ESEL code.

The work carried out through 2009 included the following items:

- The involvement in the JET work program is described in Secs. 2.2.2 – 2.2.4. It is mainly focused on modeling and simulations in addition to interpretations of experimental data. It comprises characterization and modeling of filamentary structures in the edge and SOL. Such filaments may be generated by ELM events, but does also appear in connection with blob generation.
- Investigations of the turbulence and transport at the edge and SOL of toroidal plasmas by participating in experimental investigations and applying edge/SOL turbulence codes. Turbulence and transport in this region are strongly intermittent and involve outbreaks of hot plasma in the form of density blobs formed near the last closed flux surface (LCFS), and propagating far into the SOL. They have a profound influence on the pressure profiles in the SOL and the power deposition on plasma facing components. In Sec. 2.2.6 we describe transport parallel to the magnetic field lines in the SOL initiated by blob structures, and Sec. 2.2.7 describes investigations of different parameterizations of the parallel dynamics in the ESEL model. The appearance and influence of long range correlations in the edge/SOL turbulence in toroidal plasmas is investigated by numerical simulation and qualitative agreements with experimental observations are found, see Sec. 2.2.8. Finally, Sec. 2.2.10 describes investigation of impurity transport in the SOL region modeled by tracing test particles in the ESEL code.
- The spontaneous formation of flows in turbulence is an important topic in fusion research. We have investigated various aspects of toroidal as well as poloidal flow generation and the related transport of momentum. Section 2.2.5 discusses experimental investigations of momentum transport in the SOL in ELMy H mode, with particular attention to the influence of ELMs. Section 2.2.9 presents the initial efforts in simulating turbulent momentum transport with attention to the influence of blob structures.

- To extend our turbulence modeling in the edge/SOL we are deriving gyro-fluid and gyro-kinetic models for the edge/SOL dynamics as generalizations of electrostatic, cold ion, ESEL-like models. Motivated by observations of strong time dependent radial electric fields in the edge region, the models account for both large electric fields and electromagnetic effects, see Sec. 2.2.11.
- The numerical code suite: TYR and ESEL have been upgraded by massive parallelization within the EUFORIA project as discussed in Sec 2.1.12.
- Examples of our involvement in the ITM activities are provided in Sec. 2.2.13.

2.2.1 EFDA TG tasks in 2009

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The group has during 2009 participated in the following EFDA TG tasks:

WP09-TGS-02b/01: Investigation of momentum transport in the SOL in ELMy H-mode in ASDEX-Upgrade. Evaluation of probe data and comparison with numerical simulations in collaboration with AUG, IPP, ÖAW-Innsbruck, and ENEA-RFX. See 2.2.5 and 2.2.10

WP09-MHD-04/01: Investigations of the properties of ELM dynamics by probe measurements at AUG, in collaboration with IPP, ÖAW and ENEA-RFX associations. Evaluation of data comparing magnetic fluctuations with electrostatic fluctuations for ELM filament propagation. Article submitted. See also 2.2.4, 2.2.5 and Annual report 2008 Sec. 2.2.8.

WP08-09- TGS -01b/06: Simulation studies of edge/SOL turbulence. Simulation studies of cross correlation. Data evaluation. See 2.2.9.

WP09-TGS-02c/01: Numerical investigations of impurity transport in the SOL and edge plasmas using the test particle approach in the codes ESEL and TYR. Data evaluations from turbulence measurement in the scrape-off-layer of Tokamaks under L-mode as well as H-mode conditions in collaborations with IPP, ÖAW, and ENEA-RFX. See 2.2.11.

2.2.2 Filament modelling at JET

G.S. Xu, V. Naulin, W. Fundamenski (EURATOM-CCFE Association, Culham Science Centre, Abingdon OX14 3DB, UK), J. Juul Rasmussen, A. H. Nielsen, and B. N. Wan* (*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China)*
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A consequence of blob generation and of ELM events is the existence of filamentary structures in the scrape-off-layer (SOL), but also potentially elsewhere in magnetised plasmas. Drift-Alfvén vortex filaments associated with electromagnetic turbulence were recently identified in reversed field pinch devices. Similar propagating filamentary structures were observed in the Earth magnetosheath, magnetospheric cusp and Saturn's magnetosheath by spacecrafts.

The perpendicular vortex motions and the kinetic shear Alfvén waves are coupled

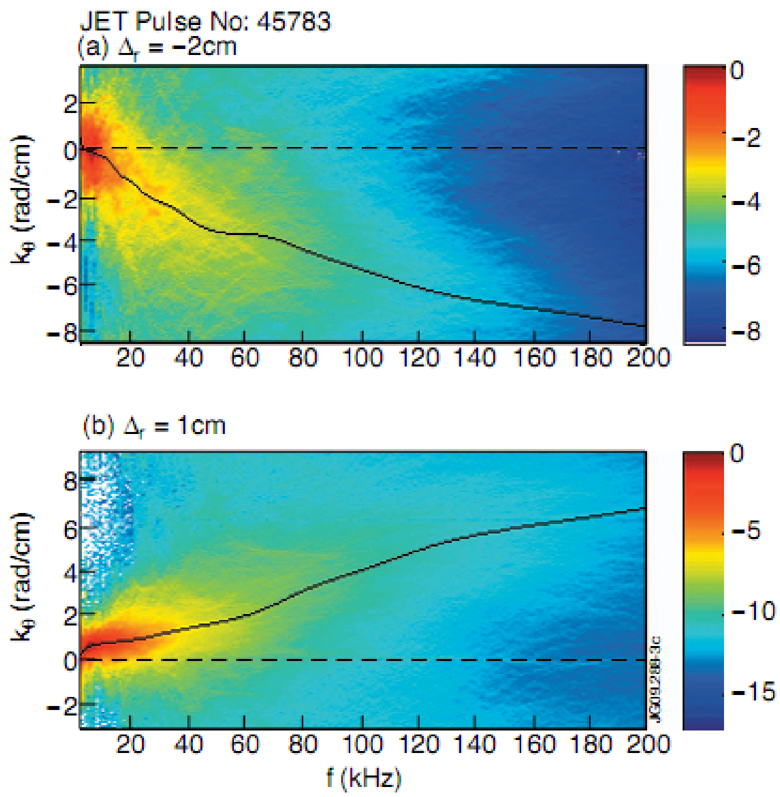

Figure 1. Power spectra ln $S(k_\theta,f)$ of floating potential fluctuations, a) inside the last closed flux surface, LCFS, and outside LCFS. The black solid line shows the dispersion relation. The results show reversal in the propagation direction of the turbulence when crossing the LCFS.

through the parallel current and Ampere's law, leading to field line bending. On the timescale of interchange motion, a thermal expansion force along the curvature radius of the magnetic field overcomes the resultant force of magnetic tension and pushes the plasma filament to accelerate in the radial direction resulting from plasma inertial response, to satisfy quasineutrality. During this process the internal energy stored in the background pressure gradient is converted into the kinetic energy of convective motion and the magnetic energy of field line bending through reversible pressure-volume work. This is resulting from the plasma compressibility in an inhomogeneous magnetic field. On the timescale of the parallel acoustic response, part of the filament's energy is transferred into the kinetic energy of parallel flow. On the dissipation timescale the kinetic energy and magnetic energy are eventually dissipated, which is accompanied by entropy production, and in this process the structure loses its coherence, but it has already travelled a significant distance in the radial direction [1]. In this way the propagating filamentary structures induce intermittent convective transports of particles, heat, current and momentum across the magnetic field. 3D simulations applying the TYR-code of these scenarios are initiated.

1. G.S. Xu, V., Naulin, W. Fundamenski, J. Juul Rasmussen, A.H. Nielsen, B.N. Wan, Phys Plasmas, **17**, 022501, (2010).

2.2.3 Blobs and holes at the edge of JET

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The existence of coherent structures, dubbed blobs, is determining for the profiles of temperature and density observed in the scrape off layer (SOL) of magnetic confinement experiments. Their intermittent occurrence and self-propulsion sets the basic properties of the SOL, crucial for predicting power loads to plasma facing components in fusion devices. Traditionally only blobs are considered, taking the form of positive excursions of density and temperature outside the last closed flux surface. The genesis of these structures is still not completely understood and the purpose of the present investigations was to understand the birth of these structures and to answer, if they are born in pairs of blobs and holes. The first experimental evidence showing the connection between blob/hole formation and zonal-flow generation was obtained in the edge plasma of the JET tokamak. Holes as well as blobs are observed to be born in the edge shear layer, where zonal-flows shear off meso-scale coherent structures, leading to disconnection of positive and negative pressure perturbations. The newly formed blobs transport azimuthal momentum up the gradient of the azimuthal flow and drive the zonal-flow shear while moving radially outwards. During this process energy is transferred from the meso-scale coherent structures to the zonal flows via the turbulent Reynolds stress, resulting in nonlinear saturation of edge turbulence and suppression of meso-scale fluctuations. These findings carry significant implications for the mechanism of structure formation in magnetically confined plasma turbulence.

2.2.4 Closed current filaments in the edge of JET

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It is now well known that ELMs lead to ejection of a number of filamentary structures into the scrap-off-layer (SOL) [1]. ELMs thus generate structures with excess energy and density and it can be conjectured that they leave corresponding holes behind. In contrast to blobs/filaments, holes are usually quickly filled by the edge plasma along the magnetic field and therefore exhibit a restricted lifetime. If such a hole, however, is able to reach a resonant surface it closes on itself, which increases its lifetime significantly. We believe that the Palm Tree Mode (PTM) is a signature of such an event. The PTM is an ELM post-cursor, which was only detected in JET type-I ELMy H-mode plasmas as long as the rational $q=3$ surface is in the ELM perturbed region [2].

Fast sampling magnetic pickup coils were used to study onset, decay and dynamics of the mode. Comparisons with charge exchange recombination spectroscopy (CXRS) show that the PTM is co-rotating with the edge plasma after the recovery of ELM induced momentum losses. Electron cyclotron emission (ECE) was used to localize the PTM, which allowed estimation of the hole current. The decay rates of the current give insight in the closing phase and the filling mechanisms, which determine the lifetime of the PTM. A diffusive transition phase from a peaked to a flat current distribution can be observed as the current filament is formed. Correlations of the lifetimes with pedestal temperatures show a linear trend, emphasizing the role of resistivity.

Palm tree modes were found to consist of a closed localized rotating current filament thus forming a magnetic island. This closed current loop is no longer in contact with the whole plasma surface and therefore has a significantly increased lifetime.

1. C. Ionita et al., J. Plasma Fusion Res. Series 8, 413 (2009)
2. H. Koslowski et al., Nuclear Fusion 45, 201 (2005)

2.2.5 Momentum transport in SOL ELMy H mode

V. Naulin, W. Fundamenski (Euratom-CCFE Association, Culham Science Centre, Abingdon, OX14 3DB, UK),, T. Versloot (FOM Institute Rijnhuizen, Association EURATOM-FOM, Nieuwegein, the Netherlands), J.J. Rasmussen, F. Mehlmann, C. Ionita*, Ch. Maszl*, H.W. Müller**, V. Rohde**, N. Vianello***, M. Zuin***, R. Cavazzana*** (*** ENEA, Consorzio RFX, Padova, Italy), M. Maraschek** (**IPP, Max-Planck-Institute for Plasma Physics, Garching, Germany) R. Schrittwieser* (*Institute for Ion Physics and Applied Physics, University of Innsbruck, Austria)*
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Investigations of radial transport of momentum have become a highly interesting topic in the last years. While in core transport the connection to ITG thermal transport and pinch effects were found, the momentum behaviour at the edge is still less well understood, even though various non axisymmetric perturbations like ripple or resonant magnetic perturbations are known to not only influence ELMs, but also the rotation of the plasma. We here investigate the relation of momentum transport before, during and after ELMs. We have performed probe measurements during ASDEX Upgrade (AUG) L-mode and H-mode shots. Simultaneously the ion density n_i and the poloidal and radial electric field $E_{\theta,\phi}$ components can be determined. From these data the three important transport parameters can be derived: radial particle flux $\Gamma = \tilde{n}\tilde{v}_r = \tilde{n}_i \tilde{E}_\theta / B_\phi$, Reynolds stress $\mathrm{Re} = \tilde{v}_r \tilde{v}_\theta = \tilde{E}_\theta \tilde{E}_r / B_\phi^2$ and the radial flux of poloidal momentum $M_r = n v_r v_\theta = n E_\theta E_r / B_\phi^2$. The latter can be split up into four contributions: $M_r = n_{i,0}\,\mathrm{Re} + v_{\theta,0}\Gamma + \tilde{n}_i \tilde{v}_r \tilde{v}_\theta + n_{i,0} \tilde{v}_r v_{\theta,0}$, where the symbols with the index "0" signify the time-averaged quantities. We have found that during ohmic L-mode shots momentum transport is mainly due to Reynolds stress, $n_{i,0}\,\mathrm{Re}$, and particle transport, $v_{\theta,0}\Gamma$. In H-Mode with large external momentum input, $v_{\theta,0}\Gamma$ and the triple fluctuating part, $\tilde{n}_i \tilde{v}_r \tilde{v}_\theta$ are of comparable size and dominate, whereas $n_{i,0}\,\mathrm{Re}$ is small and does not contribute considerably to the total transfer [1].

1. F. Mehlmann, C. Ionita, V. Naulin, J.J. Rasmussen, H.W. Müller, N. Vianello, Ch. Maszl, V. Rohde, M. Zuin, R. Cavazzana, M. Maraschek, R. Schrittwieser, and ASDEX Upgrade Team, 37th EPS Conference on Plasma Physics, Dublin, Ireland, 21 - 25 June, 2010. P1.1064

2.2.6 Steady-state and transient parallel transport in the SOL: Consequences of time-averaging of plasma parameters in the turbulent SOL

E. Havlíčková, W. Fundamenski (Euratom-CCFE Association, Culham Science Centre, Abingdon, OX14 3DB, UK),V. Naulin, A. H. Nielsen, J. Seidl*, and J. Horacek**
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A one-dimensional fluid code SOLF1D modelling parallel plasma transport in the scrape-off layer (SOL) has been developed [1]. It is based on Braginskii-like equations for electrons and ions and a fluid model for neutrals. SOLF1D is being coupled with ESEL [2], a two-dimensional turbulence code for the edge and SOL at the outboard midplane. The aim of the coupling is to improve the description of parallel losses of particles and energy in ESEL and replace a simple approximation that assumes subsonic advection and Spitzer-Härm diffusion in a steady-state simple SOL [3]. The fluid model will provide a consistent time-dependent description of parallel transport, and results show that also better agreement of ESEL simulations with experiments may be anticipated. The presented work summarizes results of SOLF1D both for steady-state and turbulent SOL. The model has been applied on data obtained by ESEL and parallel losses calculated in SOLF1D have been compared with the approximate model mentioned above. Further, we have studied the parallel dynamics in detail for a simple transient event simulating the propagation of particles and energy to targets from a blob passing across the flux tube (Fig. 2). The turbulent character of the SOL is, based on these results, anticipated to have further consequences in edge plasma modelling. In steady-state transport codes, average values of fluctuating plasma parameters are considered, often aiming to fit simulation results with statistically averaged experimental profiles. The use of average values in present-day fluid solvers can, however, lead to a misrepresentation of the dynamics between the different physical quantities, depending on the statistics of the source terms, here provided by turbulent processes at the outboard midplane. We have estimated the possible effects associated with the time-averaging of plasma parameters from data calculated by ESEL at the midplane for various radial positions and the SOLF1D code has been used to show the effect along the SOL. A steady-state solution of SOLF1D for average input parameters is compared with the corresponding time-dependent run.

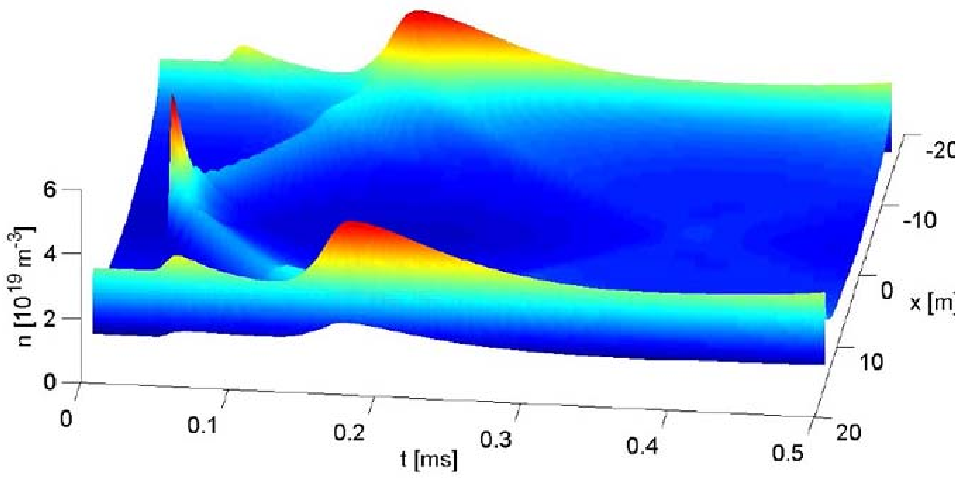

Figure 2. Propagation of plasma density, initiated as a density blob at the midplane (x=0), along the field lines to the targets.

1. E. Havlíčková, Ph.D. thesis, Charles University, Prague, 2009.
2. O. E. Garcia et al., Plasma Phys. Control. Fusion 48, L1 (2006).
3. W. Fundamenski et al., Nucl. Fusion 47, 417 (2007).

2.2.7 Investigations of parallel dynamics in the ESEL model

J. Horacek, J. Madsen, V. Naulin, A.H. Nielsen, J. Juul Rasmussen and J. Seidl* (*Institute of Plasma Physics AS CR v.v.i., Association EURATOM IPP.CR, Praha, Czech Republic)*
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The two dimensional, electrostatic edge-SOL turbulence code ESEL [1] simulates the perpendicular dynamics of transport events in the SOL together with a self consistent development of the SOL profiles at the outboard midplane. Profiles of density n, electron temperature T_e, and vorticity are evolved together with the fluctuations, without making a scale separation-ansatz, i.e., allowing relative fluctuation levels of order unity and profile variations by orders of magnitude. Parallel losses in the SOL are described by the classical sub-sonic advection, the parallel length from the midplane to the divertor/wall and Spitzer-Härm diffusion, while perpendicular collisional dissipation is approximated by Pfirsch-Schlüter neoclassical diffusivities [2].

In [1] we demonstrated that based on basic plasma parameters from TCV, results from ESEL were reproducing experimental results obtained by a reciprocating probe in the TCV SOL. These results comprise radial profiles of density, poloidal velocity and particle transport, and temporal quantities such as conditional averaged signals and the first 4 moments of the PDF's.

We have investigated the parameterization of the parallel dynamics in more details. The assumption of classical sonic advection of vorticity is at first replaced by advection with the Alfvén velocity, as discussed in, e.g., [3]. We observe that even though propagating blob structures are still produced, the blobs appear not to dominate the dynamics and the measured quantities are different from the standard case of ESEL and more important significantly different from the experimental observations. These results are consistent with assumption of low beta values in the SOL, implying that the blobs are propagating across an almost unperturbed magnetic field. When the field lines, which the blob is crossing, end on material surfaces and the parallel current associated with the blob already reaches these surfaces, then the sheath boundary conditions take over, see e.g. [3]. For highly collisional SOL conditions with detached divertor the sonic advection may describe the parallel losses reasonably, see e.g. [1]. The evolution of typical blob structures for sonic and Alfvénic parallel advection is illustrated in Fig. 3.

1. O. E. Garcia et al., Plasma Phys. Contr. Fusion 48, L1 (2006); O.E. Garcia et al., Nucl. Fusion 47, 667 (2007).
2. W. Fundamenski et al., Nucl. Fusion 47, 417 (2007).
3. G.Q. Yu, et al., Phys. Plasmas 13, 042508 (2006); S.I. Krasheninnikov and A. I. Smolyakov, Phys. Plasmas 15, 055909 (2008)

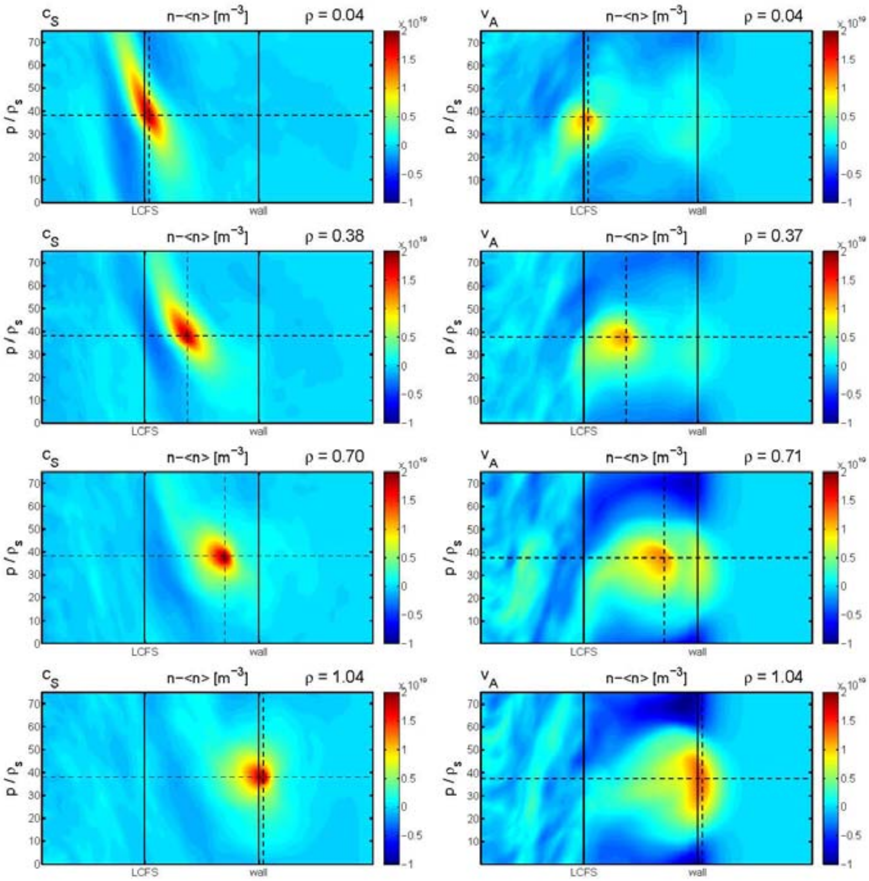

Figure 3. Conditional average density signal showing the full 2D computational domain at 4 different radial positions in the SOL and for 2 different kind of parallel velocities; C_s (left columns) and $0.5V_A$(right columns).

2.2.8 Long-range correlations in turbulent fusion plasmas

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A big challenge in operating fusion plasma devices is to control the turbulent radial particle and heat flux. It is well known that turbulence can be suppressed by a sufficiently strong poloidal/toroidal shear flows in the plasma edge region, which is connected to radial electric fields. The shear flow may be generated by the turbulence due to a self-organisation effect. However, it is also possible to establish a radial electric field and a corresponding flow by probe biasing. Recently, a strong long-distance correlation of the plasma potential fluctuations was measured during the presence of a radial electric field gradient in the TJ-II experiment at Ciemat [1]. Additionally, Silva et al [2] investigated data sets from toroidally separated probes in the ISTTOK experiment. A coupling between the Pearson correlation coefficient, C_{xy}, of large-scale potential fluctuations and the radial particle flux, Γ_p, was revealed.

The qualitative analysis of the observed coupling between C_{xy} and Γ_p in ISTTOK is the motivation of our investigations. Data from the two-dimensional interchange electrostatic turbulence model (ESEL) was used to test these results. Due to the simulation geometry the cross-correlations of potential fluctuations were computed in the poloidal direction and not in toroidal direction as in the experiment. This is not expected to have a major impact, because the shear flow acts in toroidal as well as poloidal direction, thus the nature of the observed dynamics is considered comparable.

The probe setup in the simulation consists of a central probe and three additional probes separated by 1.5, 8 and -5mm poloidally. The minus sign designates that the probe is in opposite direction of the poloidal flow. The following analyses were performed:

De-correlation time: The de-correlation time was analysed to determine the strength of the nonlinearity in the time series of the potential fluctuations and to ensure that the linear statistical tool (Pearson Correlation) can be applied. It was shown that the de-correlation times in the edge differ between the linear and nonlinear method, but in the SOL they are similar.

Extrema study: A local extrema study using Pearson Correlation and mutual information methods on the potential fluctuations and Γ_p was applied to investigate whether a high flux corresponds to a low potential fluctuation correlation and vice-versa. To compute C_{xy} at time t a subset of the potential series with $t + \Delta t$ was used. A statistical evidence of a coupling between the local extrema of Γ_p and C_{xy} was found when a small time shift (in order of the mean life time of the extreme flux events T) between the local extrema of Γ_p and C_{xy} at time t was taken into account.

Probability of the correlation coefficient: The effect of subsets of the potential series (sized Δt) on the correlation coefficient with respect to T was investigated. The extreme Γ_p events are defined as the positive tail of the 1- α quantiles of the probability distribution function, PDF, of the flux with $\alpha = 0{:}9545$. The C_{xy} distributions of the full potential data series with different subset sizes at radial positions $\rho = [0{:}0;\ 0{:}4]$ are shown in Fig. 4. At the LCFS, the probability of anti-correlated potential fluctuations at the time of an extreme flux event is high, if the subset size is smaller than the mean lifetime of the extreme event. In the SOL, the probability of uncorrelated potential fluctuations during a extreme flux event is high if the potential subsets are longer as the time between two extreme flux events, which appears to agree with the observations by Silva et al [2].

The linear correlation coefficient depends strongly on the subset size of the potential series with respect to the mean lifetime of the extreme events, especially in the SOL.

1. M. A. Pedrosa et al., Phys. Rev. Lett. 100, 215003 (2008)
2. C. Silva et al., Phys. Plasmas 15, 120703 (2008)

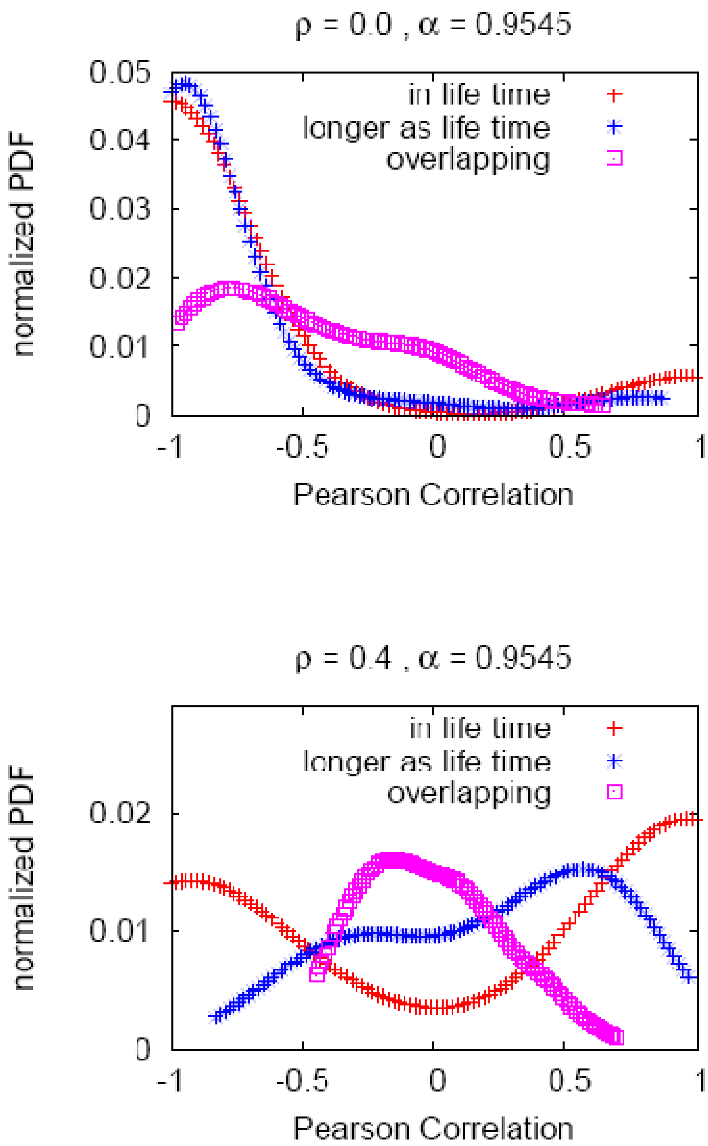

Figure 4. Distribution of the Pearson correlation coefficients of the potential fluctuations at different radial positions ρ. Red curve: The subsets $\Delta t \approx T$. Blue curve: $\Delta t > T$, but smaller than the time between two extreme flux events. Pink curve: Each subset contains information of more than one extreme event.

2.2.9 Simulations of turbulent momentum and particle transport in the Edge/SOL of magnetically confined plasma

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Turbulence is the dominating mechanism for transporting particles, energy and momentum in the edge and scrape-off-layer (SOL) of toroidal plasmas. The transport is strongly intermittent and involves large outbreaks of hot plasma. These bursts, often referred to as “blobs”, are formed near the last closed flux surface (LCFS) and penetrate far into the SOL. This applies in both Low and High confinement regimes (in the latter the bursts are related with ELMs). The Risø ESEL-code, governing the dynamics of interchange convection modes at the outboard mid-plane of a toroidal device has been successfully describing the turbulent dynamics and transport in the SOL under L-mode conditions [1].

We have here applied the ESEL-code to investigate the transport of momentum from the edge and out through the SOL. This transport relates to a momentum source/sink inducing net core rotation and the sheared flows related to the edge transport barrier. Particularly, we investigate the role of the intermittent blob structures in the momentum transport, and the relation between the particle transport and momentum transport. This is facilitated by dividing the momentum flux into passively convected - with the particles – momentum and the momentum flux arising from the Reynolds stress [2] (See Sec. 2.2.5). The main result is that blobs carry a significant amount of momentum and in this phase the passive convection is clearly dominating the Reynolds stress, see Fig. 5.

1. O. E. Garcia et al., Phys. Plasmas **12**, 062309 (2005); O. E. Garcia et al., Plasma Phys. Contr. Fusion **48**, L1 (2006).
2. J.R. Myra, D.A. Russell and D.A D’Ippolito, Phys. Plasmas **15**, 032304 (2008);

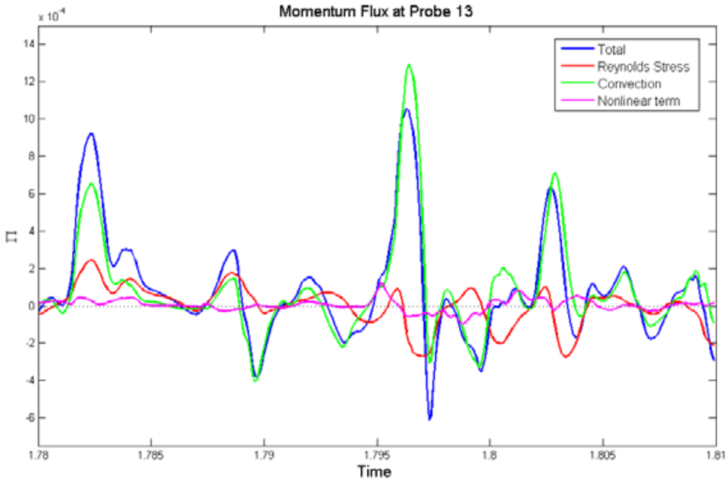

Figure 5. Time evolution of momentum flux measured in the SOL from the ESEL simulation. It is observed that the convected part of the momentum flux is dominating during blob events.

2.2.10 Simulation of turbulent impurity transport in the SOL of toroidal plasmas

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The transport of particles, energy and momentum in the edge and scrape-off-layer (SOL) of toroidal plasmas is dominantly turbulent and strongly intermittent characterized by large outbreaks of hot plasma. These bursts, often referred to as “blobs”, are formed near the last closed flux surface (LCFS) and penetrate far into the SOL. They have a significant effect on the density and temperature profiles.

For the transport of impurities in the edge and SOL region, which is of increasing concern in fusion research experiments, the turbulence plays an important role. The impurities are mainly generated at the first wall and plasma facing components, but are subsequently transported into the edge region and often all the way to the plasma centre.

We investigate the turbulent transport and mixing of impurities in the SOL by tracing test particles in the ESEL-model [1]. The impurity density is assumed to be low and the impurities are ionised, thus they can be described as particles that are passively advected by the turbulence. For light impurities the ExB velocity is dominating the impurity advection. It should be emphasized that impurity transport cannot be described by a simple diffusion process; it is strongly anomalous with step size probability distributions having broad non-Gaussian tails, with the longest steps determined by the finite width of the system (see Fig. 6). The long excursions of the particles are connected with the blob dynamics, and particularly particles may be trapped in the blob structure and carried with the blob. However, the impurities are rapidly mixed in the SOL region and the impurity density attains an "equilibrium" profile ranging into the edge of the plasma inside the LCFS. The "mixing" time is found to be only weakly influenced by the initial position of the impurities, and is only few times the characteristic period of the bursts. Thus, even particles released far into the SOL are transported inside the LCFS.

For heavier impurities inertia effects as well as finite Larmor radius (FLR) effects may become of importance. We have implemented both effects in the algorithm tracing the particles. The FLR effect is modeled by averaging the fluctuating potential over a circle described by the Larmor radius, and using this averaged potential to obtain the gyro averaged ExB velocity convecting the tracer particles. The inertia effects are modeled to the lowest order by adding the polarization drift to the ExB velocity. The FLR and inertia effects generally slow down the mixing of the impurities and also introduce compressible effects, which particularly leads to de-trapping of particles trapped in blob structures. However, the anomalous character of the transport prevails.

1. O.E. Garcia, V. Naulin, A.H Nielsen and J. Juul Rasmussen, Phys. Plasmas **12**, 062309 (2005).

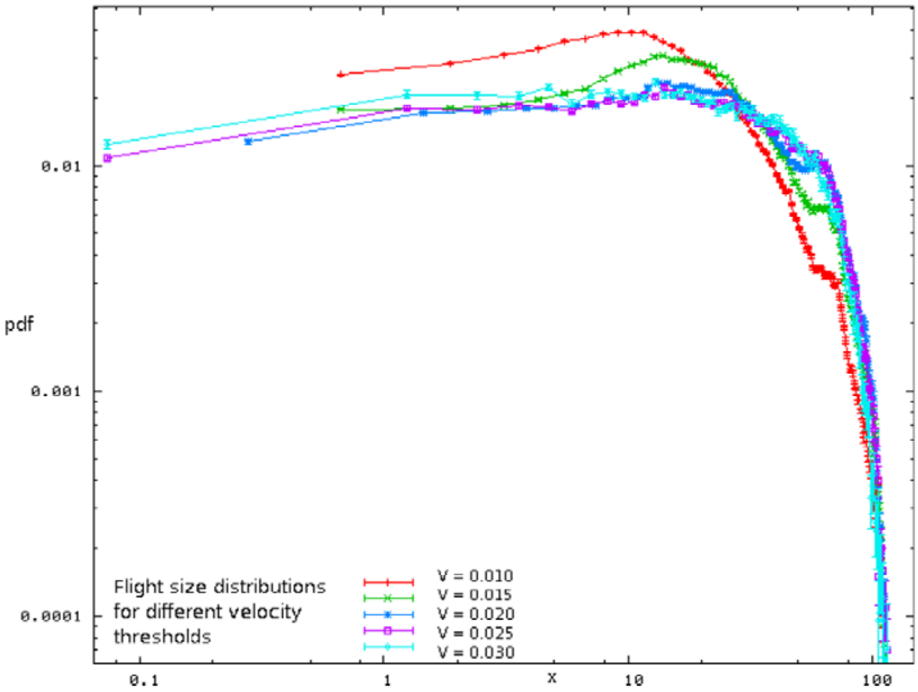

Figure 6. Step size probability distribution function for different velocity thresholds obtained by decomposing the motion into flights and waiting times. It is assumed that the tracer performs a radial excursion whenever its radial velocity is exceeding the given threshold velocity, otherwise the particle is waiting. The distance from last closed flux surface to the wall is 100.

2.2.11 Nonlinear electromagnetic gyro-kinetic and gyro-fluid model for edge/SOL

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The development of gyro-kinetic and gyro-fluid models for the edge/SOL region in toroidal magnetized plasmas is continued and extended (e.g., Annual Progress Report 2008 (Risø-R-1684) Secs. 2.2.5 – 2.2.7). In the edge/SOL region steep gradients are present in the equilibrium profiles and strong shear flows are typically observed in the pedestal and near the edge transport barrier. Furthermore, the relative fluctuation level approaches unity in the SOL. To augment our investigations of the dynamics in these regions we have derived a nonlinear gyro-kinetic model for electromagnetic fluctuations in the edge/SOL. The guiding-center coordinates in the consistent guiding-center ordering were calculated by applying the Lie transformation method to the second order. The corresponding Poisson bracket structure and equations of motion are obtained and from that the self-consistent Vlasov-Maxwell equations expressed in guiding-center coordinates are derived [1].

A gyrofluid model accounting for electrostatic perturbations in the two dimensions at the outboard midplane of toroidal devices was obtained. The model is applied to investigations of the finite ion temperature influence on dynamics of density blobs in the SOL. Initial results show that the blob structure is weakly perturbed by the finite Lamor radius effects, while the blob velocity scales with the effective ion acoustic velocity, i.e., increases with increasing ion temperature.

1. J. Madsen. Phys. Plasma, Submitted (2009).

2.2.12 MPI optimization of the numerical code suite: TYR and ESEL

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In 2007 and 2008 our 3D numerical code TYR was significantly upgraded regarding parallelization within the Euforia project (http://www.euforia-project.eu/EUFORIA), at Åbo Akademi University, Department of Information Technologies, Åbo, Finland. The TYR code simulates the drift Alfven plasma fluid turbulence and transport in a flux tube geometry. The code is implemented in C and uses MPI for message passing. The Finish group applied code optimization techniques to produce a faster code, but with the same numerical results as originally. The original version of the program implemented a spatial decomposition of a 3D grid in one dimension, the toroidal dimension, i.e., the z-coordinate of the data. This limited the maximal amount of processors that could be used to the number of points or data layers in the toroidal direction, which for a problem of ITER size typically are 128. Therefore, a new 2-dimensional decomposition has been implemented, which allows the program to efficiently take advantage of a larger numbers of processors. The result of the parallelization effort done by the Finnish group is shown in Figure 7a, where it is observed that the code is capable of using 1024 CPUs with a reasonable speedup. During 2009 the TYR code was implemented on the HPC-FF and we fine-tuned the different routines regarding MPI communication. The speedup of the effort code is shown can be observed in Figure 7b; we now have a linear speedup up to 2048 CPUs.

The ESEL code, even through quite simply in its formulations, has proven very accurate shown fine agreement comparing its results to actual experimental observations of fluctuations and transport in the scrape-off-layer of obtained data from large scale fusion experiments The code is from a numerical point of view nearly equal to TYR with the exception that the parallel dynamics are parameterized, and we thus effectively only consider regard 1 one drift-plane. It is an OpenMP C-code and it solves 3 coupled partial differential equations for the time evolution of density, temperature pressure and vorticity. Presently it is parallelized allocating each field to its own CPU, thus limiting the total number of CPUs to 3 for this code and with a speedup of approximately 2.5. During 2009 the code was like TYR being parallelized within the Euforia project at Åbo Akademi University and the code is now capable of running on 8-32 processors with a reasonable speedup. The code is presently being fine-tuned at present fine-tuning the code to optimize the MPI communications.

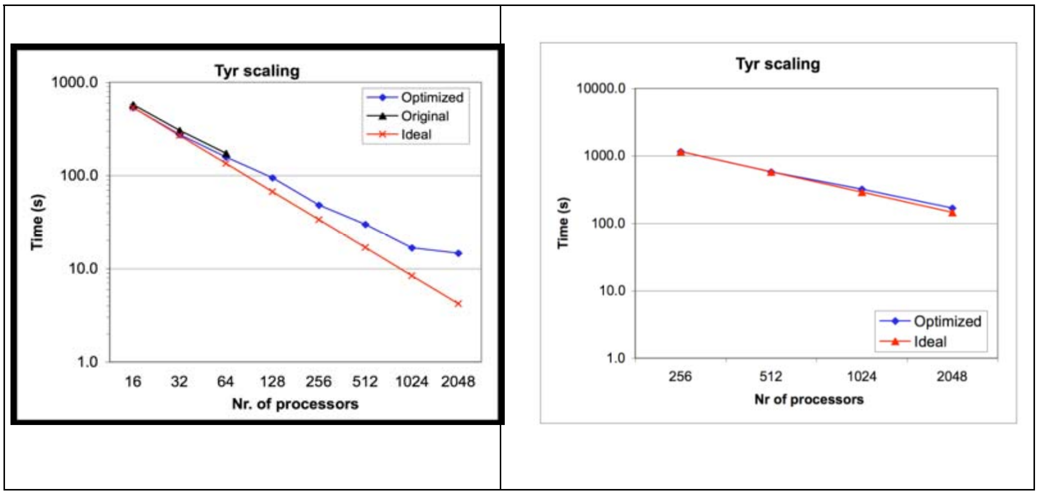

Figure 7. a) The scaling of TYR on a log-log scale for a problem size of nx=256, ny=1024, nz=64. The black line is the original version of the program, the blue line is the optimized version and the red line describes the ideal speed-up curve. b) As a) but for the fine-tuning optimization.

2.2.13 CPO interface implementation into the IMP4 turbulent codes

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ahnie@risoe.dtu.dk

The engagement in The Integrated Tokamak Modeling Task Force (ITM-TF) is focused on the project IMP4. Our contributions in 2009 have been on developing wrapper routines to be used by the different code developers in IMP4 for the major code benchmarking efforts. In 2010 IMP4 will begin the process of validation against experiments.

It is essential for IMP4 codes to be able to collect data at a central place and have it assessable to all participant. Previous work from our side has been to incorporate HDF5 as the protocol standard with the Turbulence Consistent Physical Objects, TCPO, as the content standard. The *Futils* package from CRPP/Lausanne was implemented on the Gateway with CRPP support. The TCPO was defined during the ITM General Meeting 2009.

In 2009 we established a project at the Gateway, which now contains a wrapper routine. The wrapper routine is built around the IMP4 code, ATTEMPT. At present it is not possible to submit MPI-jobs and to use CPO's simultaneously. A workaround for this is given by the modules READ_STRUCTURES and WRITE_STRUCTURES, developed by Christian Konz (IMP12). Via the routines OPEN_READ_FILE, READ_CPO and CLOSE_READ_FILE the CPO-structures can be loaded from an ASCII-file in the run directory. Furthermore, demonstration of a Kepler workflow for ATTEMPT was performed. As it is not possible to submit from Kepler to the queue system on either the Gateway or the HPC-FF, further development was put on hold until this problem is cleared by ISIP. Documentation can be found in the project cpo interface at the Gateway.

Extensible Markup Language (XML) is well defined and platform independent to handle complex parameter structures. Previously, a FORTRAN wrapper was written to read

XML files, and a C wrapper has now been developed at our department and is now being integrated into the ITM support software.

2.3 Millimetre waves used for diagnosing fast ions in fusion plasmas

S.B. Korsholm, P.K. Michelsen, H. Bindslev, V. Furtula, F. Leipold, F. Meo, D. Moseev, S.K. Nielsen, M. Salewski and M. Stejner
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Millimeter waves, corresponding to frequencies in the 100 GHz range, permit probing and imaging on the centimeter scale and transmission of signals with bandwidths in excess of 10 GHz. Coherent sources are now available from the micro- to megawatt range, CW.

In the world of fusion, millimeter waves are used extensively both as a diagnostic tool and for heating and manipulating the plasma locally as well as globally. Central to achieving these objectives is the fact that millimeter waves, like laser light, can be projected in narrow focused beams, but unlike laser light, the millimeter waves can interact strongly with the plasma.

At Risø DTU, millimetre wave diagnostics for measuring the velocity distribution of confined energetic ions in fusion plasmas are developed and exploited. The measurements have spatio-temporal resolutions on the centimeter and on the millisecond scales.

The most energetic (or fastest) ions are the result of fusion reactions and auxiliary heating. Their interaction with the bulk plasma is the main mechanism by which the fusion plasmas reach and sustain the high temperatures of 100-200 million degrees Kelvin required for fusion. The considerable energy associated with the fast ions can also drive turbulence and cause instabilities in the plasma, and hence degrade the confinement of the plasma and of the fast ions themselves. Understanding and controlling the dynamics of fast ions are central tasks in the development of fusion energy and one of the main research topics for the next large fusion facility, ITER. It is a task we seek to contribute to by developing and exploiting the unique diagnostic capability of millimeter wave based collective Thomson scattering (CTS). The importance of the fast ion CTS diagnostic was further underlined by the fact that in 2008 the front end of a fast ion CTS diagnostic system was enabled in the new ITER baseline design. In 2009 the updated ITER Baseline Design was finally approved by the ITER Council. Risø DTU has developed the preliminary design of the ITER CTS diagnostic under EFDA task agreements.

In addition to the use of CTS to diagnose fast ions, the diagnostic technique may also be used to measure the fuel ion ratio in a fusion plasma – both temporally and spatially resolved. This can be done by measuring the effect of ion Bernstein waves on the CTS spectrum. This novel use was investigate and further developed on an EFDA task, which is further described in Sections 2.3.2 and 2.3.4.

The group has developed and implemented CTS diagnostic systems at the TEXTOR and ASDEX Upgrade tokamaks, which are located at the Research Centre Jülich and at the Max-Planck Institute for Plasma Physics in Garching, both in Germany. These CTS projects are conducted in collaboration with the TEC1 consortium and the Max-Planck Institute for Plasma Physics in Garching. Up to 2008, the collaboration also included the Plasma Science and Fusion Center at MIT (USA). While they had to withdraw due to financial circumstances, the contact is still maintained.

The upgraded CTS system for TEXTOR was brought into operation in 2005 where the first results were obtained. In 2009, the experimental CTS campaigns of the previous years were continued, while the new topic of fuel ion ratio measurements was initiated. An overview of the campaigns and description of the results on TEXTOR is found in Sections 2.3.3 to 2.3.7. In addition to the CTS measurements, the Risø DTU group's involvement at TEXTOR led in 2008 to participation in a related project in collaboration with FOM. In 2009 the results of this work was published in Physical Review Letters and the project is described in Section 2.3.8. In Section 2.3.9 we describe a technology development for fast data acquisition, which has been crucial for several of the obtained results.

The CTS diagnostic system at ASDEX Upgrade was used for a number of experimental campaigns in 2008, whiles in 2009 the activities at ASDEX Upgrade by the Risø CTS group, were limited by the fact that the gyrotron was unavailable most of the year. However, important advances in the analysis techniques and analysis of the 2008 data was made during 2009. This work is presented in Sections 2.3.10 to 2.3.15. Sections 2.3.16 and 2.3.17 describe the use of the CTS receiver as an NTM tracking receiver. Finally, some effort has been invested in the preparation of a potential relocation and optimization of the CTS receiver at ASDEX Upgrade. This is described in Sections 2.3.18 to 2.3.20.

The activities of the CTS group also involved development of new techniques as well as new components. In particular the successful modeling, design, manufacturing and testing of notch filters should be noticed. This work is described in Sections 2.3.21 to 2.3.24

Finally, a brief description of the group's collaboration with the NIFS CTS group at LHD is given in Section 2.3.25.

2.3.1 EFDA tasks in 2009 for the Risø DTU CTS group

P.K. Michelsen, S.B. Korsholm, H. Bindslev, V. Furtula, F. Leipold, F. Meo, D. Moseev, S.K. Nielsen, M. Salewski and M. Stejner
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The CTS group has during 2009 participated in the following EFDA tasks:

WP08/09-DIA-01/05: Feasibility of Collective Thomson Scattering for measuring fuel ion ratio using the scattering spectrum due to ion Bernstein waves. The Risø DTU CTS group took up the responsibility for coordinating the task described in Section 2.3.2. The details of the Risø DTU work on the task are given in Section 2.3.4 and 2.3.9.

WP09-HCD-02/08: Coordinating the CTS measurements during the studies of NBI physics on ASDEX Upgrade. Participation in CTS experiments measuring fast ion distribution functions, analyze data and compare with modelling. Participation in CTS

1 TEC: The Trilateral Euregio Cluster, comprising Association EURATOM-Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Jülich, Germany; Association EURATOM-FOM, Institute for Plasma Physics, Rijnhuizen, The Netherlands; and Association EURATOM-ERM/KMS, Belgium.

experiments measuring fast ion distribution functions and work on analysis of data. Details in Sections 2.3.13 and 2.3.14.

WP09-MHD-01/01: Analyze the confinement of fast ions using CTS during Alfvénic activities measuring changes in the fast ion distribution function before and after Alfven events in ASDEX-Upgrade, in collaboration with IPP. Details in Section 2.3.15.

WP08/09-TGS-01a/01: General development of the CTS diagnostic and analysis. Definition of a detailed experimental plan on AUG. See Sections 2.3.10 to 2.3.15.

WP09-MHD-03/01: Installation of a new front end to the present CTS receiver at ASDEX-Upgrade for tracking NTM's. Using CTS on TEXTOR detailed measurements of Sawtooth behaviour. Details in Sections 2.3.16 to 2.3.17 and Section 2.3.7, respectively.

2.3.2 Fuel ion ratio task

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Recently, the issue of fuelling diagnostics has been receiving increasing attention. For the diagnostics currently in the ITER baseline design (such as the NPA) it is not clear if the fuel ion ratio can be determined within $\rho < 0.3$ [1]. The fuel ion ratio is a Group 1a measurement, i.e. measurements for machine protection and basic control. Therefore, it is of great interest to the community to develop alternative diagnostics capable of measuring the tritium to deuterium ratio. Faced with this challenge for ITER as well as for future magnetically confined burning plasmas, a coordinated effort has been initiated by EFDA aiming at developing novel diagnostic techniques for this purpose. The task has participation by FOM, VR, ENEA-CNR and Risø DTU with the latter as the task coordinator.

Generally, the investigated techniques are novel uses or further development of existing methods such as: charge exchange recombination spectrometry (CXRS) by FOM, neutron spectrometry by VR and ENEA-CNR, and collective Thomson scattering (CTS) by Risø DTU. The work encompasses modeling as well as development and testing of proof-of-principle diagnostic methods on existing devices. The task will be continued in the EFDA WP2010 with additional partners, and the aim is to compare the potential of the diagnostics and propose a potential fuel ion ratio diagnostic (set) for ITER.

2.3.3 Overview of results from CTS at TEXTOR

S.B. Korsholm, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P.K. Michelsen, D. Moseev, S.K. Nielsen, M. Salewski, M. Stejner, E. Westerhof, A. Bürger***
*(*FOM, The Netherlands, **IEF, FZJ Juelich, Germany)*
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In 2009, the exploitation of the fast ion CTS diagnostic at TEXTOR was continued, as three physics campaigns were conducted. The emphasis of the CTS campaigns was on two primary topics: Measurements of ion Bernstein waves for diagnostic development of a fuel ion ratio diagnostic and Effects of RMP on fast ion confinement. Furthermore, the experiments and increased diagnostic performance enabled the study of a phenomena observed earlier. In addition, analysis of previously obtained TEXTOR CTS data was done resulting in publications. The physics results and upgrades to the diagnostic performance are described in the sections below.

In 2009, the CTS work at TEXTOR has as always been dependent on the continual collaboration with the FOM ECRH team operating the gyrotron source and the FZJ TEXTOR team.

2.3.4 Development of a fuel ion ratio diagnostic based on CTS measurements of ion Bernstein waves

M. Stejner, S.B. Korsholm, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P.K. Michelsen, D. Moseev, S.K. Nielsen, M. Salewski, E. Westerhof, A. Bürger***
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As outlined in Section 2.3.1 development of novel fuel ion ratio diagnostics is important. CTS measurements of ion Bernstein waves (IBW) provide an alternative technique and feasibility studies have concluded that a CTS fuel ion ratio diagnostic system can meet the requirements specified for ITER and that it can be operated in conjunction with the fast ion CTS diagnostic system planned for ITER. Demonstration of the principle on current devices is the next natural step, which will test numerical predictions and provide valuable experience for the development of a CTS fuel ion ratio diagnostic.

The ability to diagnose the fuel ion ratio relies on the different properties of the IBW signatures in plasmas with different composition. Figure 8 shows theoretically calculated CTS spectra for different values of $R_H=n_H/(n_H+n_D)$ and for different scattering geometries here parameterized by the angle ϕ between the magnetic field and the resolved wave vector component. Note that the ion Bernstein wave peaks only appear in the spectrum for $\phi \simeq 90°$ and that they depend strongly on the value of R_H.

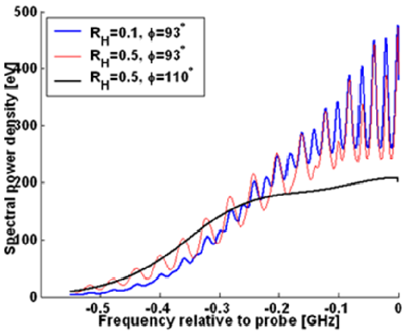

Figure 8. Theoretical spectra for different fuel ion ratios and scattering geometries.

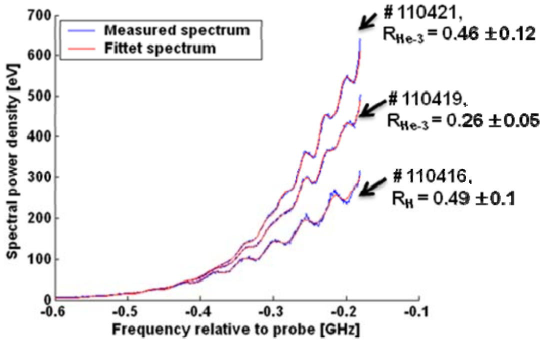

Figure 9. Measured and fitted spectra for TEXTOR discharges 111416, 111419 and 111421. Two spectra are dominated (111419 and 111421) by He-3 and deuterium and one with an equal hydrogen/deuterium mixture (111416). Inferred values and uncertainties for RH and RHe-3=nHe-3/(nHe-3+nD) are shown for each discharge. Uncertainties represent one standard deviation.

Using the fast acquisition technique described in Section 2.3.9 measurements of ion Bernstein wave signatures in CTS spectra at TEXTOR were performed for the first time in 2009. Such measurements are the basic requirement for the development of a fuel ion ratio diagnostic. Experiments were performed with hydrogen, deuterium and 3He as the main plasma ions to demonstrate sensitivity to plasma composition. Significant effort was also devoted to develop software tool s for interpretation of the measured spectra and inference of the fuel ion ratio. This is done by fitting the measured spectra with a forward model for CTS. The fitting procedure uses a Bayesian least squares approach which accounts for prior knowledge from other diagnostics about all relevant parameters. Figure 9 shows examples of measured and fitted spectra as well as the inferred fuel ion ratios and their uncertainties.

2.3.5 RMP influence on fast ion confinement

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Edge localized modes (ELM) are considered to be a challenge for the operation of ITER. Experiments on several machines during the last several years proved that resonant magnetic perturbations (RMP) applied to the edge region of the plasma attenuate or even completely eliminate ELMs. TEXTOR is equipped with the dynamic ergodic divertor (DED), a set of error field correction coils which can produce 3/1, 6/2, 12/4 magnetic field perturbations which can be rotated with various angular velocities. We wanted to study whether application of RMP affects the confinement of fast ions. In order to conclude on this influence of RMP, effects on the slow-down of fast ions were studied. We investigated the decay of signal in the fast ion channels after switching-off the co-Ip NBI in both the RMP and non-RMP phases of the discharges. Each shot was divided into two parts in which the DED coils were switched off and on, respectively. The magnetic perturbations were set externally to the 3/1 mode with no rotation.

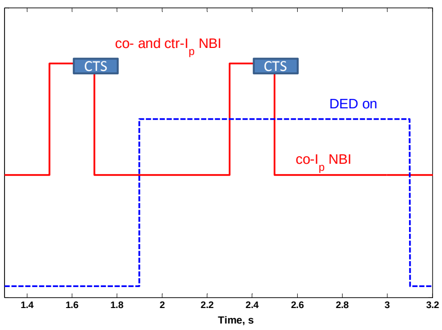

Figure 10. Schematic of the time traces of the experiments.

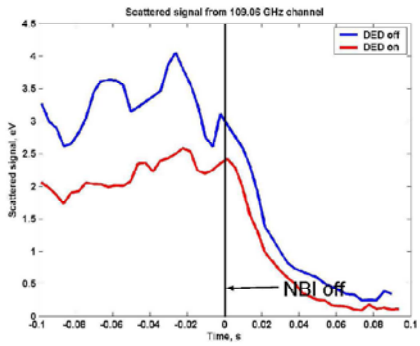

Figure 11 Evolution of scattered signal in the fast ion co-Ip channel in non-RMP (upper blue line) and RMP (lower red line) phases. The ordinate is the relative time when the NBI is switched off.

The results from 2009 were preliminary. This topic needs further experiments and investigations, particularly more experiments on resolving projections of fast ion velocity at different angles with respect to magnetic field at different radial positions in the plasma. Another problem to overcome before drawing any strong conclusion is an offset during gyrotron on time; this makes the correct analysis of scattered signal challenging. The nature of this offset is still under investigation.

2.3.6 Measurements of NBI related powerful spectral lines during NBI heating on TEXTOR

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On both TEXTOR and AUG strong scattering phenomena giving rise to very high signal level above those expected for either thermal or fast ion scattering have previously been observed during NBI start-up and in discharges with counter current NBI heating. These signals are localized in frequency symmetrically around the probe frequency and confined to a few channels in the standard CTS receiver. However, with the relatively low frequency resolution of the standard receiver it is difficult to study these phenomena. Using the high frequency resolution of the fast acquisition technique at TEXTOR (see Section 2.3.9) these phenomena can be studied in greater detail. Figure 12 shows the signal received during counter current NBI heating and Figure 13 a time resolved spectrogram showing the start-up phase for the counter current neutral beam in a different discharge.

The measurements with high frequency resolution will allow a detailed investigation of the cause for these signals. The leading hypothesis to explain the signals is NBI driven ion cyclotron instabilities similar to those found by CTS measurements on W7-AS [1].

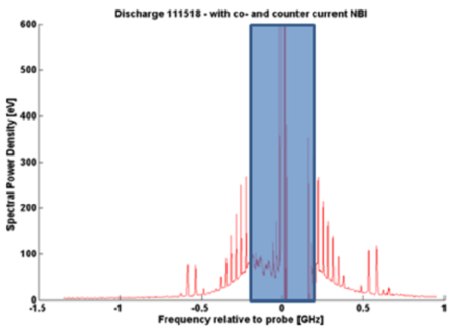

Figure 12. CTS spectrum recorded during balanced co- and counter NBI heating. The spectrum displays a number of distinct lines not otherwise seen.

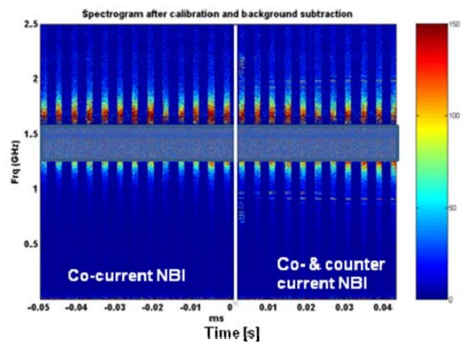

Figure 13. Time resolved spectrogram showing the startup phase of the counter current NBI. Lines appear in the spectrum at the startup and most of them subsequently fade away. The on/off modulation of the gyrotron can be seen in the spectrogram as periods of high/low signal intensity. The shaded frequency range is covered by a notch filter protecting the receiver from stray gyrotron radiation. The data in that range is not useful.

1. A. G. Shaloshov et al. (2003) Plasma Phys. Control. Fusion 45 395

2.3.7 Fast ion redistribution due to sawteeth

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First fast-ion CTS measurements in neutral beam injection (NBI) heated TEXTOR plasmas with sawtooth oscillations have been reported [1]. The measured 1D fast-ion distribution was found to drop up to 50% for resolved directions with a significant component parallel to the magnetic field due to a sawtooth crash. Furthermore, measurements in which the velocity distribution was resolved close to perpendicular to the magnetic field revealed no significant drop at the time of the sawtooth crashes. In Figure 14, the obtained velocity distributions in the plasma centre prior to and after a sawtooth crash are shown for a resolved direction at an angle φ of 127° to the main magnetic field. The crash reduces the non-thermal fast-ion population between u = 1.0•106 m/s and u = 2.5•106 m/s significantly. The time traces of the relative fast-ion phase-space densities at three different velocities are shown in Figure 15 together with the central electron temperature. A clear sawtooth behavior is evident at all three velocities.

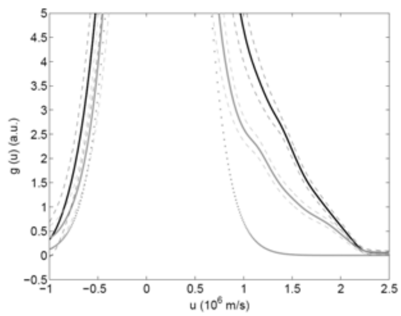

Figure 14. Ion velocity distribution just before (black line) and after (grey line) a sawtooth crash at t = 2.02 s. The error bar limits are represented by dashed lines. The bulk ion distribution (dotted line) is shown for reference.

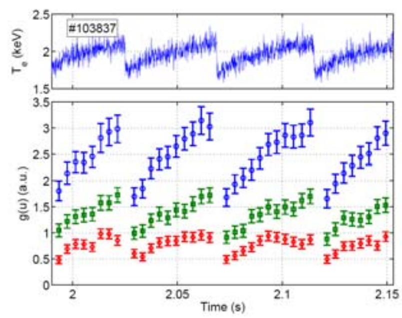

Figure 15. (top): Te from ECE, (bottom): relative fast-ion phase-space density shown for velocities 1.3 (blue), 1.6 (green),1.9 (red) •106 m/s.

In Figure 16 the time trace of the electron temperature is shown together with the integrated fast-ion distribution resolved close to parallel to the magnetic field during NBI heating. At the time of the sawtooth crash the fast-ion distribution show a drop similar to the distribution described in Figure 14 and Figure 15. In Figure 17 the electron temperature and the integrated fast-ion distribution resolved close to perpendicular to the magnetic field is shown. Here no evident drop in the fast-ion features is observed. This indicates a pitch angle dependence of the fast ion redistribution due to sawteeth crash.

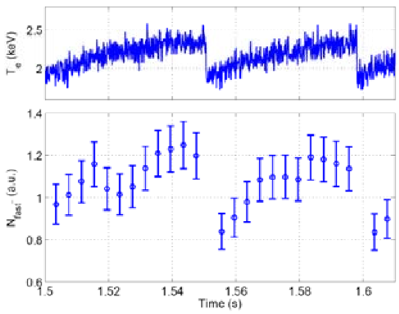

Figure 16. Top: central electron temperature. Bottom: fast ion density resolved 39 degrees to B.

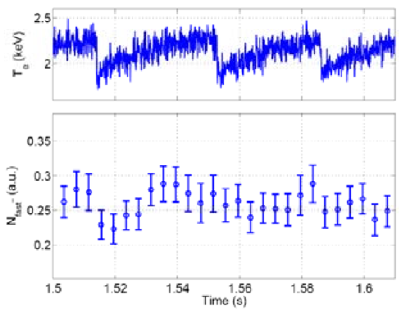

Figure 17. Top: central electron temperature. Bottom: fast ion density resolved 83 degrees to B.

1. S. K. Nielsen, H. Bindslev, M. Salewski et al., submitted to Phys. Rev. Lett. (2010).

2.3.8 Island studies during 140 GHz gyrotron operation

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The collaboration with FOM has been extended regarding the investigation of microwave scattering of plasma waves during periods with rotating islands in the TEXTOR plasmas. An upgraded radiometer sharing the transmission line of the gyrotron and an upgraded CTS receiver were used to diagnose the strong scattering observed. The phenomena have now been observed using both the high power 140 GHz gyrotron and the 110 GHz gyrotron as probe radiation. The experimental setup is shown in Figure 18.

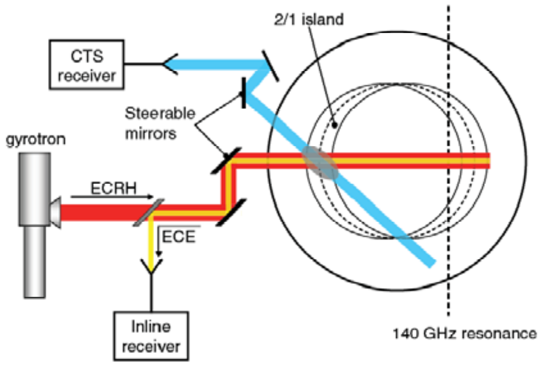

Figure 18. Setup of experiment

The scattering occurs only in plasmas with a (rotating) m = 2, n = 1 tearing mode within a well-defined range of densities. In particular, the scattering occurs during passage of the island O-point through the ECRH beam on the low-field side of the tokamak (see Figure 19). It depends sensitively on the density and shows a strongly nonlinear dependence on the ECRH power. This correlation of wave scattering with a tearing mode has not been foreseen by any existing theory, and no explanation has been found to date.

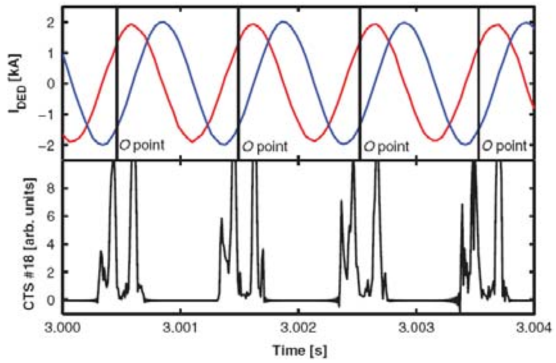

Figure 19. Current of external coils shown in top together with the passing time of the island O-point. At the bottom a time trace of a channel in the CTS receiver is shown.

1. E. Westerhof, S. K. Nielsen et al., Phys. Rev. Lett. 103, 125001 (2009)

2.3.9 Development of a fast acquisition technique for CTS measurements

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The standard acquisition technique for CTS measurements at TEXTOR and AUG relies on splitting the signal into several band pass limited channels, the bandwidth of which defines the frequency resolution of the measurement. The power level in each channel is then measured by ADCs with 24 bit resolution. This provides a highly sensitive acquisition over a very large dynamic range but with relatively poor frequency resolution – typically the channel band width is around 80 -100 MHz. The standard acquisition technique is well suited for measurements of fast ion populations, but, for several other applications of CTS higher frequency resolution is required and significant effort has been devoted to develop an alternative acquisition technique at TEXTOR to meet this demand.

To provide the high frequency resolution an additional heterodyne down conversion step is included in the TEXTOR CTS receiver and the down converted CTS signal is directly digitized by use of a Tektronix Digital Phosphor Oscilloscope (model DPO 7104). The recorded spectrum is then Fourier transformed to extract the CTS spectrum at a resolution of 0.6 MHz (though note the resolution is variable and could be much higher). The high sampling rate (up to 20 G samples/s) and large memory (200 MB) of the oscilloscope are critical to the ability to perform such measurements while its 8 bit resolution and 1 GHz analogue bandwidth limit the energy resolution and bandwidth of the acquired spectrum. The specifications for such oscilloscopes are expected to improve in the near future allowing further development of the technique. It should further be noted, that significant effort has also been devoted to eliminate sources of noise and standing waves in the receiver, to develop software tools for background subtraction and interpretation of the measured signal and to develop procedures for calibration of the measured spectra.

The fast acquisition technique has been used to measure the signature of ion Bernstein waves in the CTS spectrum. Such measurements are a basic requirement for the development of a CTS fuel ion ratio diagnostic which is among the candidates to measure the composition of ITER plasmas. The technique has also allowed detailed measurements of strong scattering phenomena in TEXTOR related to NBI start-up and counter-current NBI. The high frequency resolution was critical in demonstrating the strong scattering consists of individual and well separated lines in the CTS spectrum. The fast acquisition technique has further been used in support of fast ion CTS measurements where the high frequency resolution will enable more accurate interpretation of parts of the measured spectra.

The fast acquisition technique developed at TEXTOR is a versatile tool, which has already allowed access to new physics phenomena previously inaccessible with the standard acquisition technique. In the future fast acquisition is expected to become a permanent feature of the CTS receiver at AUG to supplements the standard acquisition technique and in particular to continue the development of the fuel ion ratio diagnostic.

2.3.10 Overview of the CTS at ASDEX Upgrade

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P. K. Michelsen, D. Moseev, S. K. Nielsen, M. Salewski, M. Stejner, J. Stober, G. Tardini*, D. Wagner*, and the ASDEX Upgrade team*
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The CTS diagnostic installed on ASDEX Upgrade uses the 1 MW dual frequency gyrotron as the probe. The 105 GHz frequency mode is used as the probing radiation where power up to 620 kW for 10 seconds has been attained. CTS experiments were not possible in early 2009 due to the gyrotron vacuum problems in March. The gyrotron was then shipped for repair. A new dual frequency gyrotron was scheduled to arrive at IPP by the fall 2009. Hence, in close collaboration with IPP Garching, preparation for the CTS campaign was carried out where scenario development was needed for comparisons of fast ion measurements between CTS, NPA, and the newly installed fast ion D-alpha (FIDA) diagnostic. Unfortunately, due to technical problems with the newly arrived gyrotron, 105 GHz operation in the fall of 2009 was not possible. However, 2009 was marked by significant progress in the analysis of the data collected in 2008.

A plan for moving the CTS receiver and quasi-optics from the MOU box to the NBI control room has been work-out in close collaboration with the ECRH group at IPP. This will enable changing the CTS receiver line between waveguides (antenna) and thus not being dependant on one particular gyrotron as the CTS probing source. In addition this will also enable the flexibility to choose an antenna that will result in a larger scattering angle hence a smaller scattering volume size but compromising the overlap (decreasing scattering signal).

2.3.11 Analysis of secondary emissions in the raw data

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The CTS data from ASDEX Upgrade H-mode plasmas contained some unexpected signals not related to scattering that required additional analysis and treatment of the data. Significant progress was made in analysis of the data from 2008 in close collaboration with IPP. These secondary emission (SE) signals, previously called “spurious signal type A”, are generated from the plasma-gyrotron interaction and therefore contain additional physics. Despite their existence that complicates the fast ion analysis, they do not prevent the diagnostic's capability to infer the fast ion distribution function on AUG. [1]. Different diagnostics from different locations in the tokamak have been correlated to the secondary emissions. Three types of secondary emissions have been identified each appearing under different experimental conditions and hence believed to be created by different physical mechanisms. The first type, which is the most prevalent secondary emission in CTS experiments in AUG H-mode discharges, is correlated to ELMs. Shown in Figure 20, the SE signals appear as spikes during the gyro-on periods (in red) and show a clear correlation with the rise of the bolometer signal (shown in black) during an ELM event. These SE-ELM mainly affect the central channels (3 - 5 channels ± 500 MHz on either side of the gyrotron line). The occurrence and intensity of SE-ELM decrease for channels further away from the gyrotron line and can be asymmetric in frequency. One hypothesis is local heating of ELM filament structures that pass through the $2\Omega_e$ layer in front of the ECRH antenna as they propagate outward. The ELM filaments can carry a significant portion of the pedestal density and can absorb a portion of the gyrotron power when crossing the resonance layer. The high energy electrons created re-emit radiation detected by the neighbouring receiver antenna at μs time scales due to the low confinement time because of to the high parallel conductivity. Regardless of the physics mechanism behind their creation, SE-ELM signals can be avoided in principle by triggering the gyrotron shortly after an ELM is detected by the diode bolometer camera located in the same sector as the ECRH antennae.

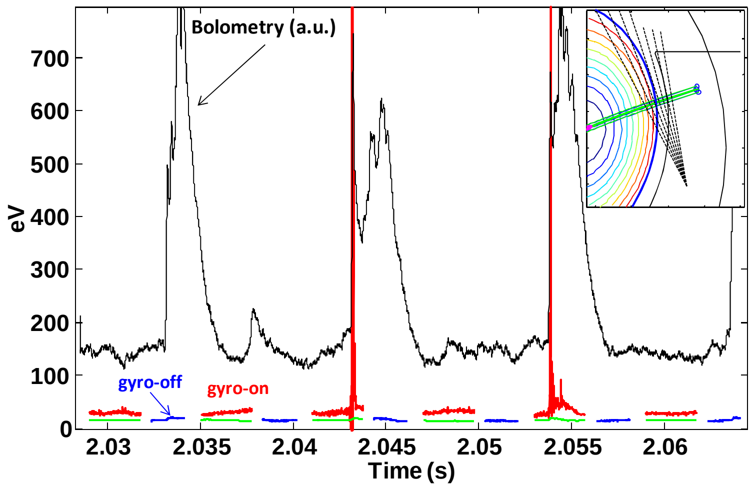

Figure 20. Time trace of CTS raw data sampled in a channel about 400 MHz away from the gyrotron line in an H-mode AUG discharge #23939. Red curves represent samples taken during gyrotron periods (gyrotron-on, CTS + ECE), while blue are samples taken during ECE periods (gyrotron-off, ECE only). The green lines are the reconstructed ECE level during the gyro-on periods. The black curve is the raw signal from the outermost viewing channel of the bolometer diode camera located at the same sector as the CTS probe and receiver. The viewing geometry of the bolometer is shown as the dotted lines in the schematic in the insert.

The second type of SE appears when the NBI ion sources near perpendicular to the magnetic field and appears at distinct channels on either side of the gyrotron line (see also Section 2.3.6). These signals are present regardless of the antennae position and overlap and are believed to be from lower hybrid (LH) instability driven turbulence created by perpendicular fast ions. This was also observed on the CTS at W7-AS stellarator [2]. The third type of SE appears when ion cyclotron resonance heating (ICRH) is present. Experiments were carried out where a portion of the heterodyned IF signal (via a 3dB coupler) was fed to a Tektronix Digital Phosphor Oscilloscope (model DPO 7104) with a fast 120 Mbyte memory frame grabbing capability and 1 GHz bandwidth. The spectrogram shows distinct harmonic structures that follow the gyrotron frequency chirp and the drift due to thermal expansion of the gyrotron cavity. The frequency difference between each harmonic is about 36.5 ± 0.5 MHz, which is equal to the ICRH generator frequency. This was also seen on TEXTOR experiments [3]. This suggests a non-linear wave mixing between the gyrotron and the ICRH waves. This interaction is likely to be located in the edge region where parasitic absorption of ICRH waves exists, thus creating rectified sheaths on opened field lines.

Challenges inherent to the CTS-AUG such as secondary emissions in the raw data necessitated additional study and analysis in order to attain the fast ion information. This was possible due to the non-random nature of the SE signals in frequency (unlike the secondary emissions from the gyrotron itself). In some instances, the exclusion of entire channels was required in the inference procedure. Preliminary studies have shown that the exclusion of certain channels does not significantly affect the determination of the fast ion distribution function.

1. F. Meo et al J. Phys.: Conf. Ser. submitted (2010)
2. E .V. Suvorov et al, 1998 Nuclear Fusion, 38 (1998) 661-671
3. P. P. Woskov et al, Rev. Sci. Instrum. 77 (2006) 10E524

2.3.12 Upgrade of analysis tools for background subtraction in CTS data from ASDEX Upgrade

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The ability to measure fast ion velocity distributions by CTS relies among other things on accurate procedures for subtraction of Electron Cyclotron Emission (ECE) background from the signal measured by the CTS receiver. The spectral power density of the background can be tens of eV while the fast ion signal is on the order of a few eV, so the background subtraction procedure must be highly reliable. For TEXTOR CTS data a highly successful background subtraction technique has been developed in which the gyrotron probing beam is modulated in a 2 ms on / 2 ms off cycle. The background measured during the gyrotron off periods is then interpolated and used to predict the background during the gyrotron on periods. On AUG, which unlike TEXTOR can access the high confinement plasma mode, additional complications arise because ELMs modulate conditions near the plasma edge, which is where the ECE background comes from. This gives rise to strong fluctuations in the ECE background on timescales short compared to the 2 ms on / 2 ms off gyrotron cycle. This complicates the background subtraction and it was found necessary to develop new software tools to subtract the ECE background.

The new procedures rely on the same gyrotron modulation cycle as previously but are better able to account for the fluctuating conditions at the edge. The background is predicted as a function of a number of parameters by calculating correlation coefficients between these parameters and the background measured in a given CTS channel during gyrotron on times. Relevant parameters used to predict the ECE background include plasma position and density, current in the divertor probes and the signal measured in receiver channels which are sufficiently far removed in frequency from the probing frequency that no CTS signal is expected. The correlation coefficients vary over time as conditions near the edge change and are therefore continuously re-evaluated to match conditions relevant to each gyrotron pulse. The new procedures have been tested on data taken without probing radiation and they were found to significantly improve the background subtraction relative to the methods developed for TEXTOR. Sufficient accuracy was achieved to enable studies of the fast ion velocity distribution on AUG, and continued development of the codes should further improve their accuracy.

2.3.13 Fast ion distribution results for NBI heated plasmas on ASDEX Upgrade

F. Meo, M. Salewski, M. Stejner, H. Bindslev, S. B. Korsholm, V. Furtula, F. Leipold, F. Leuterer, P. K. Michelsen, D. Moseev, S. K. Nielsen, J. Stober*, G. Tardini*, D. Wagner*, and the ASDEX Upgrade team*
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The analysis of CTS data taken from preliminary experiments in low triangularity NBI heated plasmas in late 2008 has enabled the first fast ion distribution results. These first results have already uncovered some physics of confined fast ions near the plasma centre with off-axis neutral beam heating. ASDEX Upgrade is equipped with an array of different NBI ion sources with different beam line geometries including on-axis and off-axis capability. It was already shown in AUG experiments that off-axis NBI current drive has unveiled deviations from the classical picture under certain operating regimes even in the absence of MHD instabilities. The reason is thought to be redistribution of fast ions due to turbulence [1]. Figure 21.(a) and (b) show results of the spectral power density and confined fast ion distribution function respectively for an NBI heated H-mode plasma. The graphs compare two NBI heating configurations using on-axis and off-axis ion beam sources (P_{source} = 2.4 MW). The error-bars shown in Figure 21.(a) are one standard deviation of a number of spectral power densities during each heating phase.

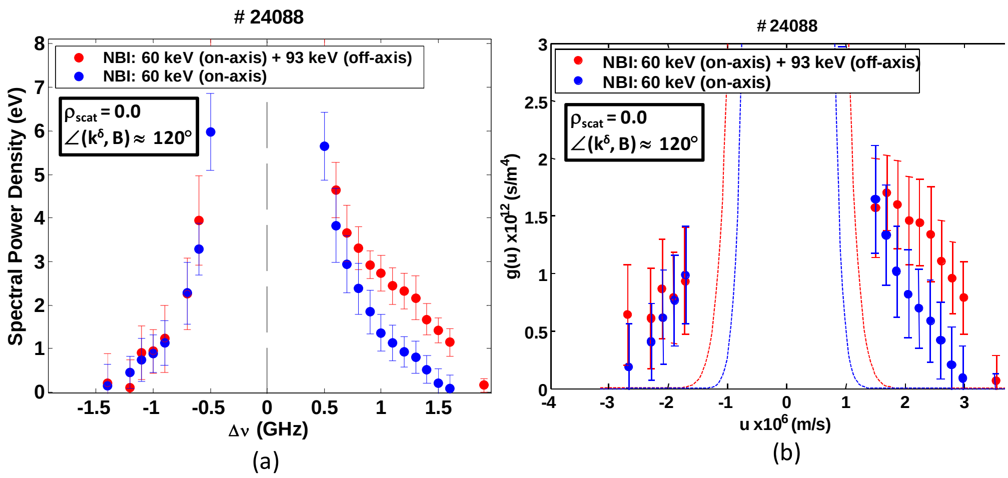

Figure 21. The CTS results; the red/blue data points on both graphs represent NBI heating configuration with two/one ion sources. (a) Spectral power density and (b) fast ion distribution function for a low triangularity standard H-mode plasma with $n_e(0) = 6 \times 10^{19}$ m^{-3}, Bt = 2.6 T. The abscissa in (a) is the frequency and in (b) is the velocity component along k^δ. The g(u) in Figure 2(b) is the projection of the velocity distribution function $f(v_{/\!/}, v_\perp)$ along the direction of k^δ. More details are described in Reference [4].

The scattering volume is located at the centre of the plasma with $\angle(k^\delta, B) \approx 120°$ where Ip and B are anti-parallel. The dashed lines are the bulk ion distribution.

The inferred one-dimensional fast ion velocity distribution functions are clearly asymmetric as a consequence of the anisotropy of the beam ion populations and the selected geometry of the experiment. In this scattering geometry, the scattering volume is located near the plasma center and k^δ is oriented in the same toroidal direction as the plasma current (Ip). Figure 21.(a) shows the frequency up-shift due to the fast ion flow direction as expected from $\omega^\delta \approx v_{ion} k^\delta$. These first results show that an off-axis beam source has a significant effect on the fast ion distribution function in the plasma center.

1. Günter S. et al Nucl. Fusion 47 (2007) 920–928

2.3.14 CTS measurements compared to simulations

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In collaboration with IPP and TEKES, fast ion distribution results from CTS of NBI heated AUG discharges have been compared to two different simulation codes [1]. Figure 22 shows this comparison of the same discharge in two heating phases using ion sources of similar beam line geometries but different injection energies. As expected, the fast ion results from CTS in the one-beam and the two beam configuration are clearly distinguishable. In addition, a difference in distribution shape can be seen between the two heating configuration of different beam sources of different injection energies, which is expected according to the simulation. We observe some agreement between the ASCOT and TRANSP/NUBEAM simulation codes in experimentally accessible parameters. However, it may be possible to find a heating scenario for which the two codes make different predictions, and which could be experimentally distinguishable by CTS. This will require some benchmarking efforts among the codes features of the measured spectral power densities and one-dimensional fast ion velocity distributions. However, quantitative discrepancies in absolute values and gradients were observed which will drive future activities in the development of the diagnostic and the codes.

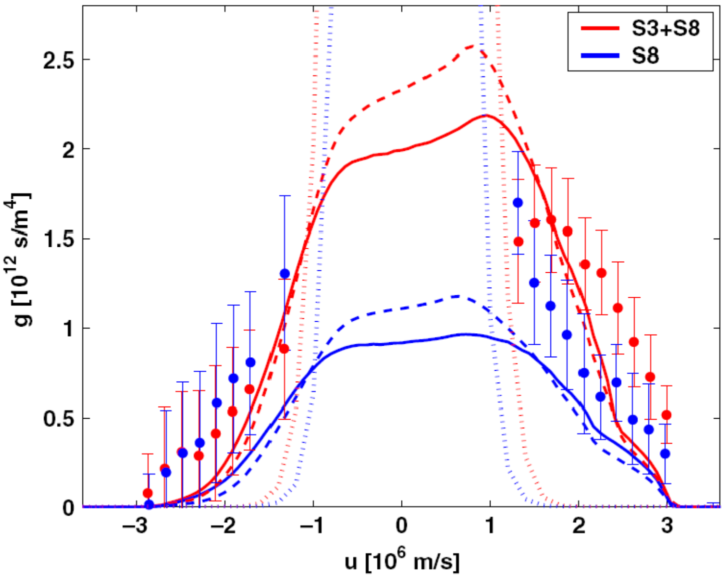

Figure 22. Comparison of the measured and computed one-dimensional fast ion velocity distribution g(u) for plasma heating by two beams (60 keV + 93 keV, red) and one beam (93 keV, blue). Solid line results from TRANSP/NUBEAM, dashed from ASCOT and the dotted line is the bulk ions.

1. Salewski M et al, 2010 Nucl. Fusion **50** 035012

2.3.15 CTS during Alfvénic activities

F. Meo, H. Bindslev, M. Garcia-Munoz, V. Furtula, S. B. Korsholm, F. Leipold, F. Leuterer*, P. K. Michelsen, D. Moseev, S. K. Nielsen, M. Salewski, M. Stejner, J. Stober*, G. Tardini*, D. Wagner*, and the ASDEX Upgrade team*
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As mentioned in the overview section, due to technical problems with the 105 GHz operation of the duel frequency gyrotron, no CTS data was available in 2009. However, in close collaboration with IPP, scenario development of AUG discharges were carried out where early NBI heating during the ramp up phase was applied to drive Alfvén Eigenmodes (AE). NBI driven Alfvén Cascades and Toroidal AE were observed. In 2010 is planned to study the redistribution of fast-ions in the presence of NBI and ICRH driven AEs with the CTS diagnostic.

2.3.16 Receiver upgrade for detection frequency between 135 to 145 GHz

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In order to detect NTM signals, the CTS receiver was upgraded for the possibility to be sensitive in a frequency range between 135 and 145 GHz. Therefore, the front end including mixing unit needed to be replaced. The mixing unit was designed in a way that the signal range was converted to the same intermediate frequency (4.5 GHz – 14.5 GHz). The schematic of the front end including mixing stage is shown in Figure 23. The operation of the system was tested by launching the 140 GHz gyrotron at ASDEX Upgrade. Stray radiation of the gyrotron could be observed. The notch of the notch filter did not coincide with the gyrotron frequency. The notch filter therefore needs retuning.

An in house built notch filter was employed. For this test, the 105 GHz horn antenna was used.

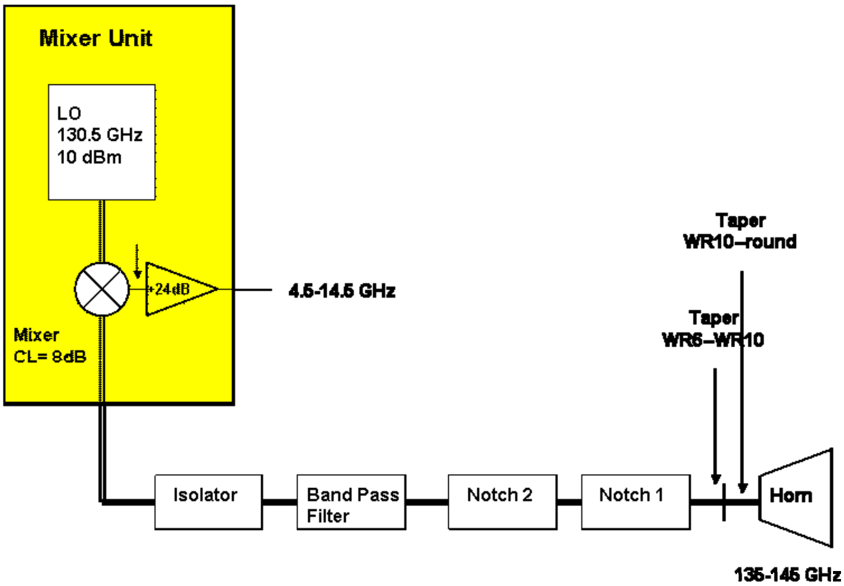

Figure 23: Front end and mixing unit for detecting capability between 135 and 145 GHz

2.3.17 First measurements of NTM's for feedback control

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The CTS receiver has the potential to detect and locate NTM with high spatial precision. This requires modification of the CTS receiver from a 105 GHz based system to a 140 GHz based one. Section 2.3.16 describes more in detail the technical features of the changes. Preliminary experiments using the 105 GHz front end and the 140 GHz based detection system were carried out in a standard H-mode plasma. An NTM scenario has been developed in collaboration with IPP. In addition, the experiments included the detector antenna sweep across the 3/2 surface during an NTM phase in order to detect the movement of the O-point between channels. Risø DTU has also successfully designed and constructed a 140 GHz based notch filter with impressively low insertion loss (Section 2.3.22). The 140 GHz notch filters were designed to have a broad 1 GHz wide notch to attenuate all of the 5 gyrotron at AUG. Each of the 140 GHz gyrotrons has slightly different frequency to within a few hundred MHz. The required hardware delivery from microwave companies was delayed and only delivered toward the end of 2009 year. Nonetheless, proof of principle experiments were carried out. However, one of the heating gyrotrons, routinely used by AUG, has a frequency of about 700 MHz lower and hence outside the notch filter. This extra non-absorbed stray radiation from this particular gyrotron saturated and disrupted many of the measurements. In addition, NTM excitation during the experiments was also transient and additional power was not possible because of divertor heating limitations.

2.3.18 Design of a new quasi optical receiver transmission front end for the CTS at ASDEX Upgrade

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It is planned for 2010 that the ASDEX Upgrade CTS receiver will be moved from the gyrotron hall to the NBI control room. This will enable changing the CTS receiver line between waveguides (antenna) and thus not being dependant on one particular gyrotron as the CTS probing source. In addition to removing the dependence of one particular probe, this will also enable the flexibility to choose an antenna that will result in a larger scattering angle hence a smaller scattering volume size (increased spatial resolution) but compromising the overlap (decreasing scattering signal). The gyrotron transmission line has to be intercepted by means of an RF switch (see sections below). In the ECRH mode the switch will transmit the gyrotron beam to the tokamak. When the RF switch is set to CTS-mode, the radiation from the tokamak is transmitted into a quasi-optical transmission line, consisting of 4 mirrors and 2 polarizer plates, which convert the elliptically polarized wave into a linear polarized wave suitable for reception by a corrugated horn antenna. The receiver has also to be upgraded in order to detect NTM signals at a frequency of 140 GHz through the same transmission line. Therefore, the quasi-optical transmission line is designed for two frequency ranges with center frequencies of 105 GHz and 140 GHz, respectively.

2.3.19 RF switch in the new optical transmission line for the CTS receiver on ASDEX Upgrade

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The schematic below shows the principal operation of the RF switch. The housing has 3 (optional 4) ports which are in the same plane. A piston inside the housing can be moved perpendicular to that plane and rotated (90 degrees) around an axis perpendicular to the plane. The piston has a straight hole through in the upper plane and a mitre bend in the lower plane. The 4 positions are sketched in Figure 24 below. The gyrotron is looking into the tokamak in the piston-down position, while the CTS system is looking into the tokamak or into the gyrotron box when the piston is in the up position.

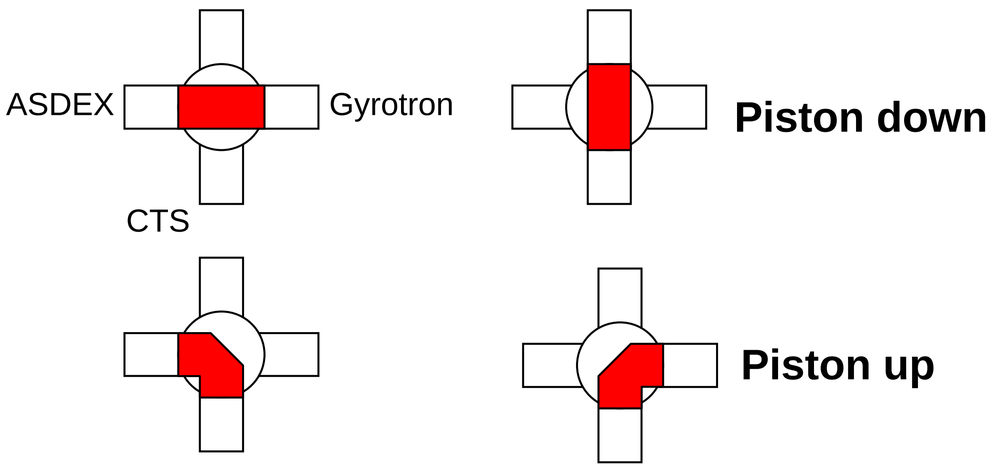
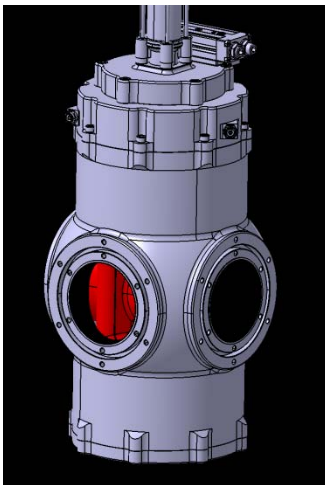


Figure 24: Schematic of the RF switch

A round piston is a straight forward solution where the piston has two positions in axial displacement and 2 positions in rotation around the axis. The CATIA drawings are shown in Figure 25. The switch is designed to operate pneumatically.

a) 

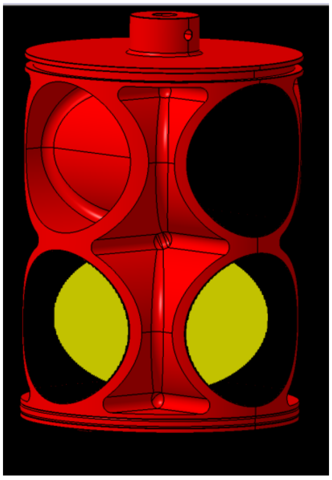
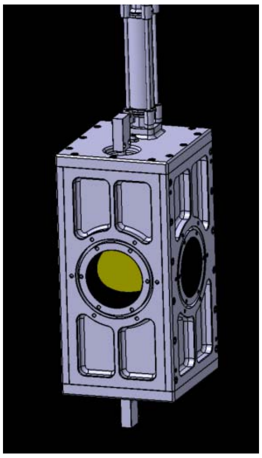
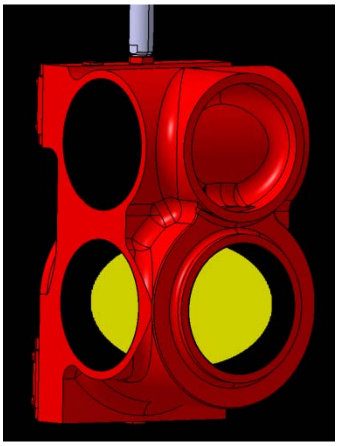
b) 

Figure 25: a) Housing of the switch with the piston (red). b) Piston inside the switch. The lower level contains the mitre bend mirror (yellow). The upper level is just a hole through.

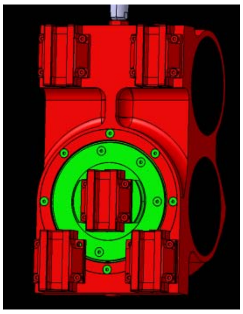
This solution requires a curved cut which also means a cut of the corrugations inside the hole under an angle. Since no experiences about the microwave behavior under these conditions are available, the requirement was set to a plane cutting surface perpendicular to the axis of the wave guide; only a rectangular piston can be used. This constraint made the design more complex. The CATIA parts are shown in Figure 26.



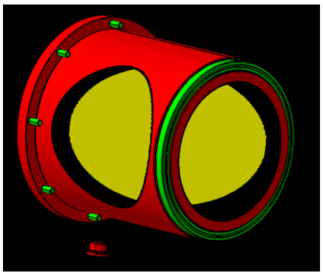
a) Housing of the switch with a rectangular piston. The mirror of the mitre bend can be seen (yellow).



b) Rectangular piston. The lower level contains the mitre bend mirror inlet (yellow). The upper level is just a hole through.



c) Rectangular piston seen from behind. The green part is a rotating inlet containing the mitre bend mirror to allow a switching between tokamak and gyrotron box



d) Rotating inlet (red) with mitre bend mirror (yellow)

Figure 26 a-d: RF switch with rectangular piston

The piston is rectangular, so the cutting plane for the gyrotron position is perpendicular to the axis of the waveguide. The position "CTS" has two transitions. One transition with a plane cut perpendicular to the axis and a second one with a curved cut. This is because the piston has an inlet which can be rotated. This design meets the requirement given by ASDEX Upgrade for the gyrotron operation and allows us to switch the CTS receiver between the tokamak and the gyrotron box.

2.3.20 Outline of the new mirror optics unit for the CTS receiver on ASDEX Upgrade

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The radiation coming from the tokamak is transmitted from the corrugated transmission line to the optical transmission line. It is assumed that the beam is Gaussian with the waist at the exit port and a waist radius of 28.31 mm. The exit port is at position 1. The positions refer to Figure 27 and Figure 28 . The red beam shown in the CATIA drawing in figure 4 corresponds to the 105 GHz beam where the border is 1.6 times the Gaussian width of the beam. This size ensures that the radiation is caught to 99.4%. The 140 GHz beam lies inside the 105 GHz beam and is not depicted here. The mirrors at position 2 and 3 are flat and serve as alignment mirrors. They are therefore omitted in Figure 28. The mirror at position 4 (Mirror 1) is curved and focuses the beam in the middle between the polarizer plates at position 5 and 6 (Polarizer 1 and 2). The optical path length from position 1 to position 4 is chosen so that the beam waists for both beam frequencies coincide between the polarizer plates. The mirror at position 7 (Mirror 2) is curved and refocuses the beam in order to make it acceptable for the corrugated horn antennas at position 8. Mirror 2 can be rotated so the beam can be directed in either of the two horn antennas, designed for 105 GHz or 140 GHz, respectively. The intercept mirror can be inserted into the beam line and direct radiation form a hot source (position 11 hot) or a cold source (position 11 cold) into the horn antenna for calibration.

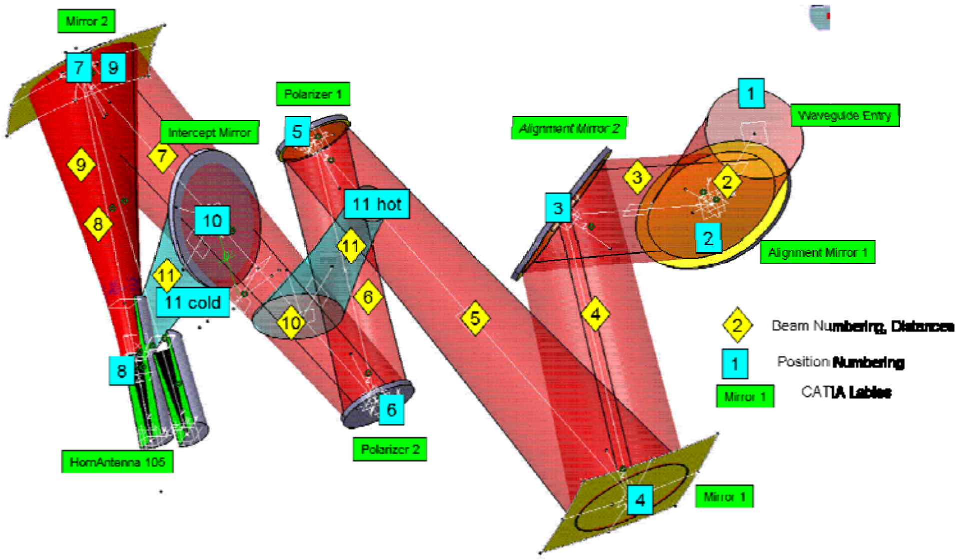

Figure 27. Transmission line. The beam is shown in red and represents 1.6 times the Gaussian width.

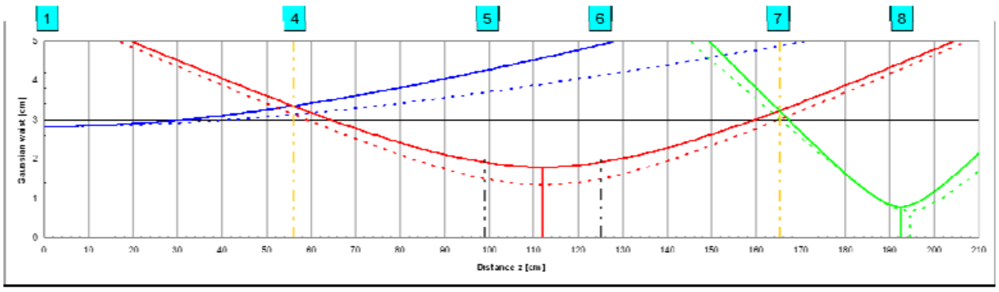

Figure 28. Beam radius of the microwave travelling through the quasi-optical transmission line. The blue labels correspond to the labels in Figure 27. The solid lines correspond to 105 GHz and the dashed lines correspond to 140 GHz.

In order to verify the calculated mirror shape, the propagation of the beam is simulated in MatLab. Figure 29 shows the modeling. The modeling was performed for 2 frequencies, 105 GHz and 140 GHz. The modeled beam dimension coincides with the dimension used for the mirror calculations.

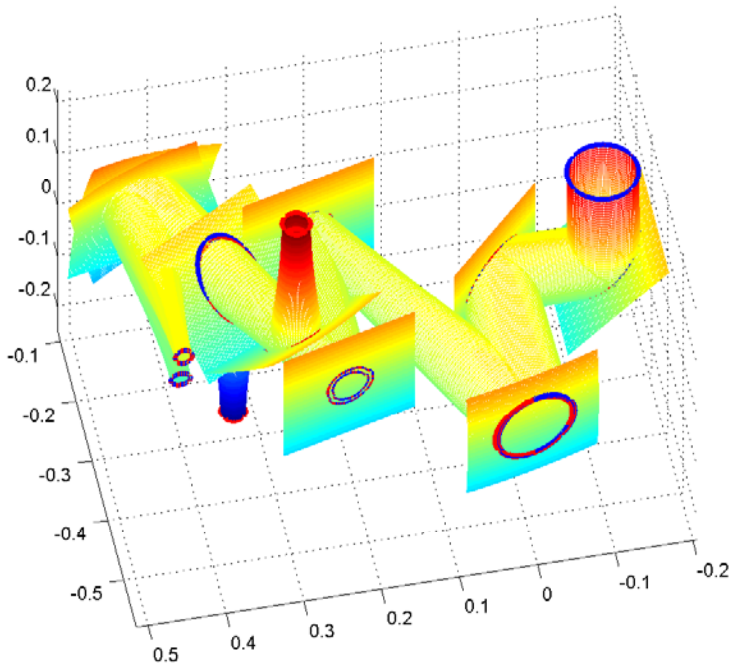

Figure 29. Modeling of the beam propagation.

2.3.21 Voltage controlled variable attenuator tests

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Due to the non-absorbed radiation scenario inherent to CTS, ECE is usually turned off during the CTS experiments in order to protect the ECE mixer. The goal of the VCVA is to attenuate the ECE line during a gyrotron pulse where stray radiation is large hence enabling the use of ECE measurements during CTS experiments. In collaboration with DTU Elektro, measurements show an insertion loss of below 3 dB throughout the entire ECE bandwidth at a room temperature of 22 °C. Experiments were also carried out at Risø DTU in order to test the VCVA insertion loss as a function of ambient temperature. The experimental setup consisted of a 3dB coupler splitting an RF source into two transmission lines; the VCVA and to a bypass line. The VCVA temperature was varied using an advanced thermal temperature controller. Results in Figure 30 show that the attenuation increases by 0.4 % per °C.

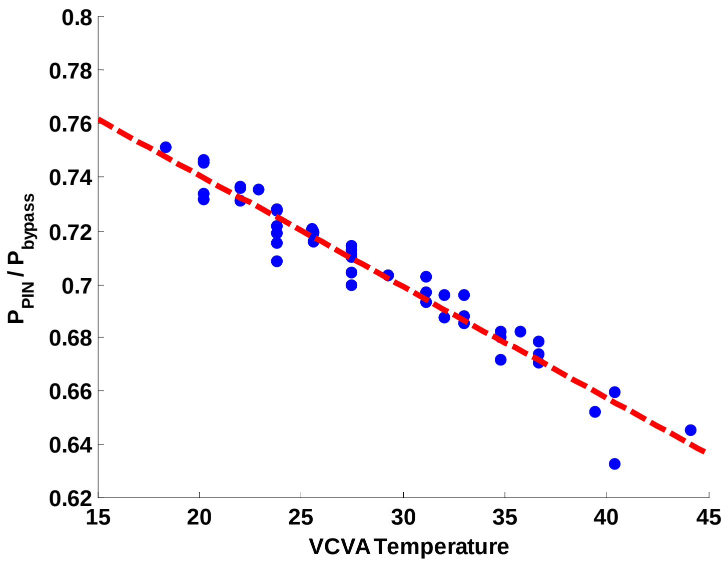

Figure 30. Ratio between the transmitted power through the VCVA and the power through the bypass line as a function of VCVA temperature.

2.3.22 140 GHz notch filter for CTS/ECE

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Notch filters are widely used in plasma diagnostic systems to prevent high power stray radiation from damaging or saturating the sensitive microwave components installed in mm-wave receivers. This kind of filter is not commercially available. A 140 GHz notch filter with 1 GHz rejection bandwidth (3 dB points) and 30 GHz passband bandwidth has been simulated designed and constructed. The filter characteristics were measured in collaboration with IFP-Milan using a D-band vector network analyzer (VNA) (see Figure 32). The notch filter is made to protect the 140 GHz CTS receiver. Another application of this notch filter is to protect the ECE receiver from the CTS gyrotron stray radiation.

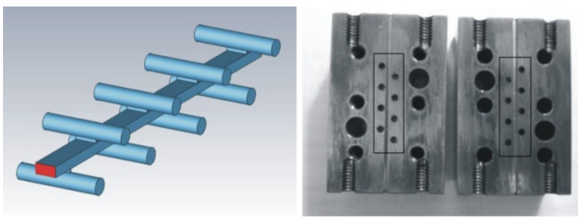

Figure 31. The filter design consisting of a waveguide and 8 cylindrical cavities (left). The flat surface in red colour is the connection port. The mechanical blocks milled out from two mirrored parts (right). The two blocks confine 8 cylindrical cavities giving rise to a single notch with rejection better than 50 dB (see Figure 32).

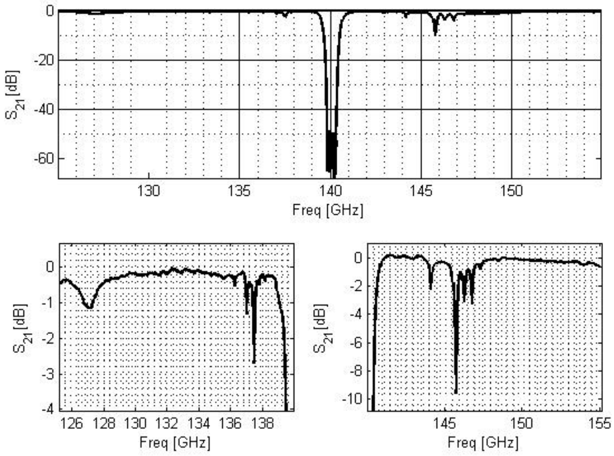

Figure 32. The S-parameters measured at IFP-Milan. The *down-left* and *down-right* figures show the filter passband on the left-hand side and on the right-hand side of the center frequency, respectively.

2.3.23 105 GHz notch filter for CTS/ECE

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A 105 GHz notch filter with 1 GHz rejection bandwidth (3 dB points) and around 20 GHz passband bandwidth has been simulated, designed, constructed and measured at Risø DTU. The application of this notch filter is to protect the ASDEX Upgrade ECE diagnostic system. The measurements are performed by using a commercial 20 GHz VNA, first up-converting the VNA output signal (port 1) and then down-converting the signal to the VNA input (port 2). The setup (see Figure 34) is calibrated by attaching a straight waveguide (WR-8) piece and applying the through calibration routine programmed in VNA. The other components used are straight waveguide pieces, waveguide bends, two isolators and a highpass filter (HPF) to reject all the lower harmonics. The output S-parameter is presented in Figure 33 showing rejection better than 50 dB with bandwidth of 220 MHz.

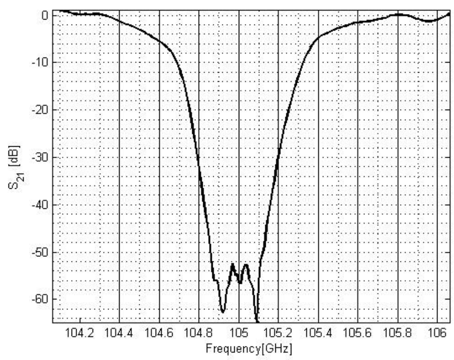

Figure 33. The S-parameters of the notch filter measured at Risø DTU

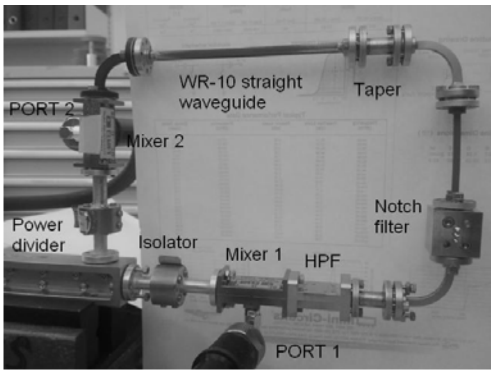

Figure 34. The notch filter test setup.

2.3.24 140 GHz MMIC for a CTS receiver

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MMIC's, or Monolithic Microwave Integrated Circuits, are a novel type of integrated circuit (IC) device that operates at microwave frequencies (300 MHz to 300 GHz). These devices typically perform functions such as mixing, high amplification, low noise amplification, and high frequency switching. Inputs and outputs on MMIC devices are matched to a characteristic impedance of 50 Ohms. This makes them easier to use in large systems, since cascading of MMIC's does not then require an external matching network. Most microwave test equipment is designed to operate in a 50 Ohm environment. MMIC's are dimensionally small (from around 1 mm^2 to 10 mm^2) implying that losses are easily controlled and noise levels are relatively limited. Historically, MMIC's were fabricated using gallium arsenide (GaAs), which is a III-V compound semiconductor that use group V atoms in the periodic table of elements as donors and group III atoms as acceptors. It has two fundamental advantages over Silicon (Si), the traditional material for IC realisation: transistor speed and a semi-insulating substrate. Both factors are important for the design of high frequency circuits. GaAs is the compound expected to be used for integrated receiver design.

Other III-V technologies, such as Indium Phosphide (InP), Silicon Germanium (SiGe), Gallium Nitride (GaN) exist. Which one to use is a trade-off among design parameters like gain, cutoff frequency, noise level, transistor speed, operation temperature, and wafer size.

Initial technology investigations on microwave monolithic integrated circuits (MMICs) suitable for CTS receiver system have been performed. CTS relevant frequencies are 140 GHz (for studying neo-classical tearing modes on ASDEX), 105 GHz (ASDEX) and 60 GHz (ITER). The most challenging design frequency is 140 GHz. A possible open foundry service to use is the French company Ommic, since they offer a process named D007IH for D-band applications. DTU Elektro, who is also a part of this project, has good connections to Ommic.

Simulations in Advanced Design System (ADS) using simple coplanar transmission lines and a single FET transistor have been performed. The first results seem to be promising, with low noise figure (NF) and good return loss. More complicated circuits with many transmission lines and several FETs are inevitable in the case of CTS MMIC receiver design. The next step is to confirm whether Ommic process D007IH is sufficient for CTS applications.

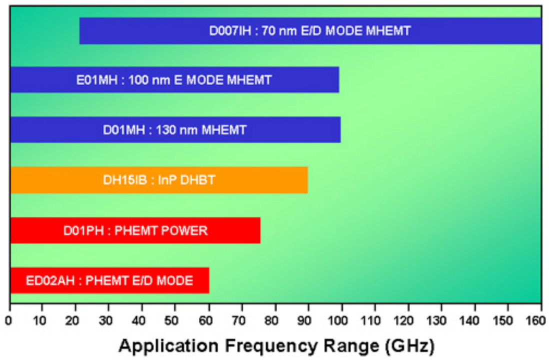

Figure 35. Typically the OMMIC processes are used from 800 MHz to 150 GHz and from low MB/s to 80 GB/s.

2.3.25 Collaboration with the CTS team at LHD

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During the fall 2009, the CTS NIFS team from Toki, Japan invited two Risø DTU CTS team members to finalize the commissioning of the CTS diagnostic on LHD and to take part in experiments. The CTS system at LHD uses an existing 77 GHz gyrotron, which probes between the fundamental resonance and the second harmonic. Significant improvement was made to the receiver and successful experiments were carried out. In addition, continued collaboration resulted in benchmarking the groups' scattering codes.

2.4 Publications

International journal publications

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3 Fusion Technology

3.1 In-Situ synchrotron x-ray scattering and magnetization study of coated conductor high temperature superconductors

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Summary: The Risø-DTU work program on superconductivity of 2009 consisted of two tasks:

1. In-situ studies of the phase and texture formation of $REBa_2Cu_3O_{6+x}$ (RE = rare earth) on metal substrates using sol-gel deposition techniques. The motivation is to obtain a fast and cheap method for producing the coated conductor superconductors for the TF coils of DEMO.
2. Measurements of the magnetic relaxation of a coated conductor from Superpower in order to provide irreversibility field and dynamic properties of the tape in applied fields up to B = 16 Tesla exceeding the target field B = 10-14 Tesla of the DEMO coils.

The in-situ high energy synchrotron studies of texture and phase transformations in coated conductor high temperature superconductors formulated in the Risø-DTU 2008 work programme were terminated as part of the Risø-DTU contribution to EUROATOM after recommendation from the EFDA 2008 review meeting 21 April 2009. The focus of the EFDA activities on high temperature superconductivity should be on the application of commercial available coated conductors and not on the development of the conductors them self.

Magnetization measurements on commercial coated conductors from Superpower have been initiated in 2009 as preparation for the HTS4Fusion program of EFDA and preliminary results are reported here. In summary it is concluded that the critical current density of a tape with I_C = 80 A in self field at T = 77 K (State of the art in 2008) will not be able to support a supercurrent at the DEMO target of B = 10-14 Tesla at T = 77 K when the applied field is along the normal of the tape. However sub-cooling of liquid nitrogen to T = 65 K will improve the properties of the coated conductor and operation in B = 10 Tesla will be possible. Magnetic relaxation studies of a superpower coated conductor have been initiated and the dynamic phase diagram of the tape has been obtained. The dynamic phase diagram indicates the energy scale U_0 of the pinning centers holding the flux lines compared to the thermal energy scale k_BT through the so called S-value, $S = d \ln J / d \ln t \approx K_BT / U_0$. It is concluded that the S values will be of the order 0.4-0.5 at B = 10-14 Tesla and T = 65 K, whereby the transition from the superconducting to the normal state will be more smooth than for the low temperature operation of the coated conductors.

In-situ synchrotron studies

The in-situ activities were finalized by performing an experiment on 1) the phase transformation of bulk pellets of Nd- and $SmBa_2Cu_3O_{6+x}$ sol-gel used for the dip coating deposition of the superconductor precursor and 2) a room temperature texture study of an $YBa_2Cu_3O_{6+x}$ thin film deposited on a LSAT single crystal substrate in order to examine if the higher harmonics of the synchrotron wiggler at the high energy beam line BW5 at

HASYLAB[1] could be reduced using a thermal gradient monochromator instead of a Si/Ge concentration gradient monochromator.

The sol-gel bulk pellets were pressed from a dried precursor solution of Sm/Nd($CH_3CH_2COO)_3$, Ba($CH_3CH_2COO)_2$ and Cu($CH_3CH_2COO)_2$ mixed in a ratio of 1:2:3 in propionic acid. The phase transformation was studied by heating the pellets in the synchrotron furnace in an atmosphere of 100 ppm O_2 in Ar while collecting 2D diffraction patterns on a MAR-345 image plate detector at the high energy beamline BW5 at HASYLAB[1]. Figure 36 shows the time evolution of the diffraction patterns of a Sm-123 bulk sol-gel pellet when the sample was heated to T = 920 ^{o}C. The diffraction pattern reveals that Ba($CH_3CH_2COO)_2$ is easily decomposed into $BaCO_3$, which remains as a secondary impurity phase during the entire reaction. The superconducting phase formation starts after approximately 20 minutes after the temperature set point is reached and is complete approximately after 100 minutes of dwell time. The final Sm-123 phase is contaminated by $BaCO_3$, which is undergoing a crystalline phase transformation around 800 ^{o}C. It was concluded that the bulk samples most likely have a much larger diffusion path of the O_2 compared to the thin films and that a study of the influence of the pellet thickness should be done. The texture experiments showed that the thermal gradient monochromator did reduce the content of higher harmonics of the direct beam.

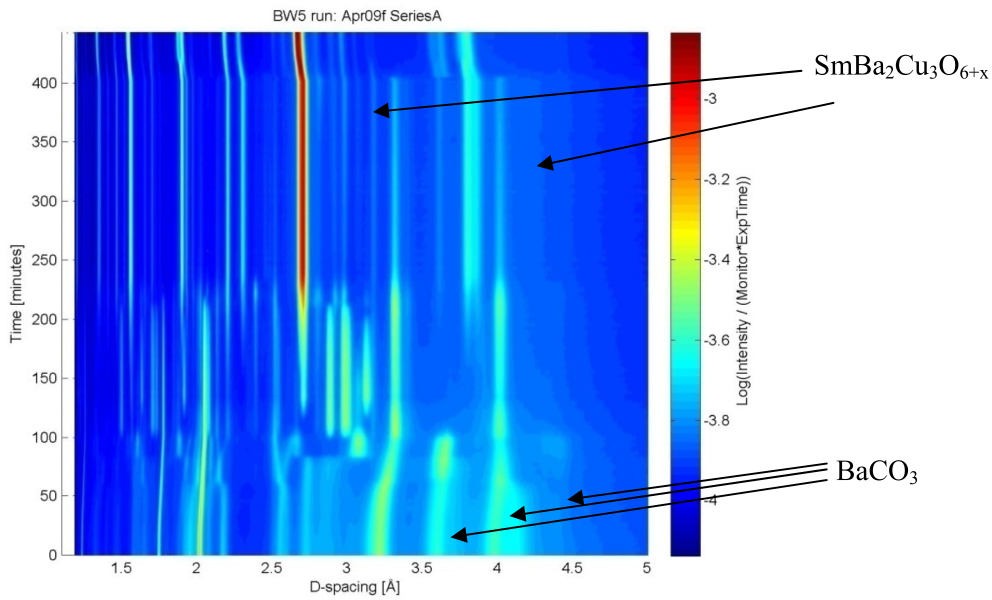

Figure 36. Time evolution of diffraction pattern from bulk pellet of Sm-123 sol-gel when heating up to T = 920 ^{o}C followed by a dwell of 300 minutes and a final cooling to room temperature.

Magnetization relaxation studies of coated conductors

The Materials Research Division of Risø-DTU has recently obtained a Cryogen Free Measurement System (CFMS) [2], which can measure the magnetization of samples cooled down to T = 2 K and in applied magnetic fields up to B = 16 Tesla. Magnetization measurements on commercial coated conductors from Superpower have been initiated on 4 mm x 4 mm pieces of tape and by applying the magnetic field perpendicular to the tape plane. Figure 37 shows a typical magnetization curve obtained by changing the magnetic field in steps of 0.5 Tesla and with a rate of 0.5 Tesla/minute followed by a waiting period, where the relaxation of the magnetic moments is recorded.

One can then determine the critical current density J_C from the opening between the magnetization curves sweeping the applied field up and down by applying the Bean model [3]. The irreversibility field $B_{irr}(T)$ is found when the critical current vanishes, $J_C \rightarrow 0$.

The dynamic response of the flux lines in the superconductor was examined by determining the decay rates of the magnetic moment and thereby also the decay of the critical current density as function of time as shown on figure 38. The initial relaxation is govern by the stabilization of the power supply of the superconducting magnet of the CFMS, but it is followed by as fast and then slower decay rate in the time scale of t = 60-10000 seconds. The fast decay rate is expected to provide the dynamic response of the superconductor, where the flux lines are still redistributing, whereas the slow decay rate corresponds to a frozen flux line distribution only govern by thermally activated flux line movements. Thus we propose a hypothesis that the n-value of the transport properties of the superconductor should be derived from the initial fast decay rate, whereas the critical current density should be derived from the extrapolation to t = 0 of the slowly decay magnetization.

Figure 39 shows the dynamic phase diagram of the coated conductor with a contour plot of the relaxation rate as function of operation temperature and applied field. Additionally the irreversibility line is showing where the current density of the superconductor vanishes. The s-values can be correlated to the n-value obtained in a transport measurement characterization of a coated conductor, where the electric field along the tape is given by $E = E_0\ (J/J_0(B,T))^n$ with $E_0 = 10^{-4}$ V/m and J_0 is the critical current density of the tape at a given field and temperature. In the case of the single-vortex pinning regime one would expect n = 1/s [4] and one thereby obtain n ~ 1/ 0.06 = 17 at T = 77 K and B = 0.1 Tesla, which is good agreement with the n= 15 supplied by Superpower. Thus it seems that the magnetization measurements can be used to determine the transport properties of the tape, but further work must be done to determine if the simple relation between s and n is also valid at high fields B = 10-14 Tesla.

Conclusion

The in-situ synchrotron experiments on phase and texture formation of coated conductors has been terminated and measurements on relaxation of the magnetic moments of commercial coated conductors from Superpower has been initiated. The irreversibility line, the critical current density and the relaxation rate of an I_C = 80 A (self field at T = 77K) tape (state-of-the-art 2008) has been determined and the dynamic phase diagram of the tape has been constructed. We have concluded that T = 77 K operation will not be possible in B = 10-14 Tesla, but sub-cooling of liquid nitrogen will provide the superconducting state. The magnetic relaxation of the Superpower tape will be s ~ 0.5 in the operation window of the DEMO magnets B = 10-14 Tesla and T = 65 K, whereby the deviation from the superconducting state will be less abrupt compared to low temperature operation such as s ~ 10 at T = 10 K and B = 10 Tesla. The dynamic properties of the tape can be use to evaluate the quench properties of the superconductor in a coil.

There reported results is expected published as part of the work on the Superwind project at DTU [5].

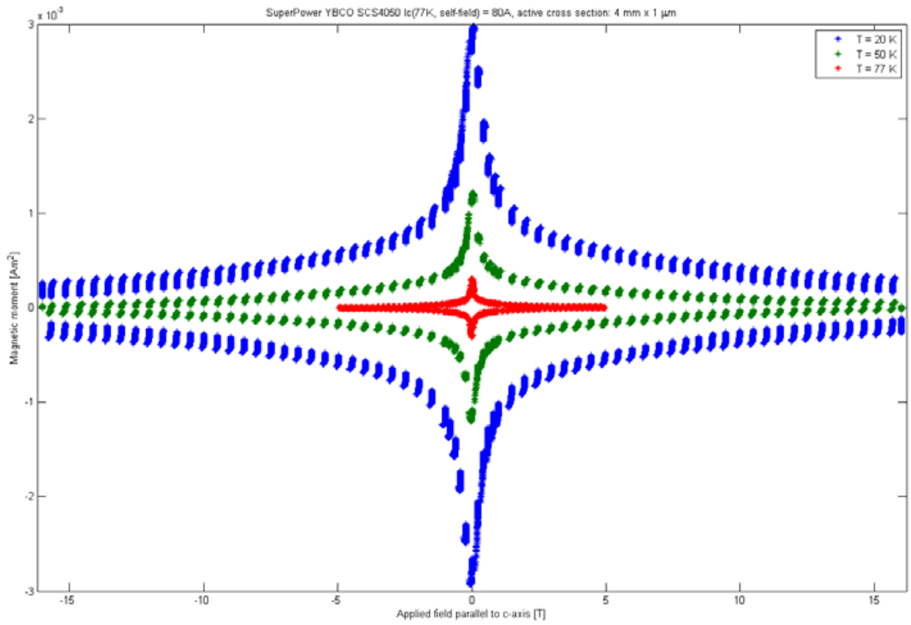

Figure 37. Magnetization curve of coated conductor obtained by stepping the applied field by 0.5 Tesla and then recording the relaxation of the moment for 150 second before next field step. This gives information about the critical current density as well as the flux dynamics of the coated conductor at different fields and temperatures.

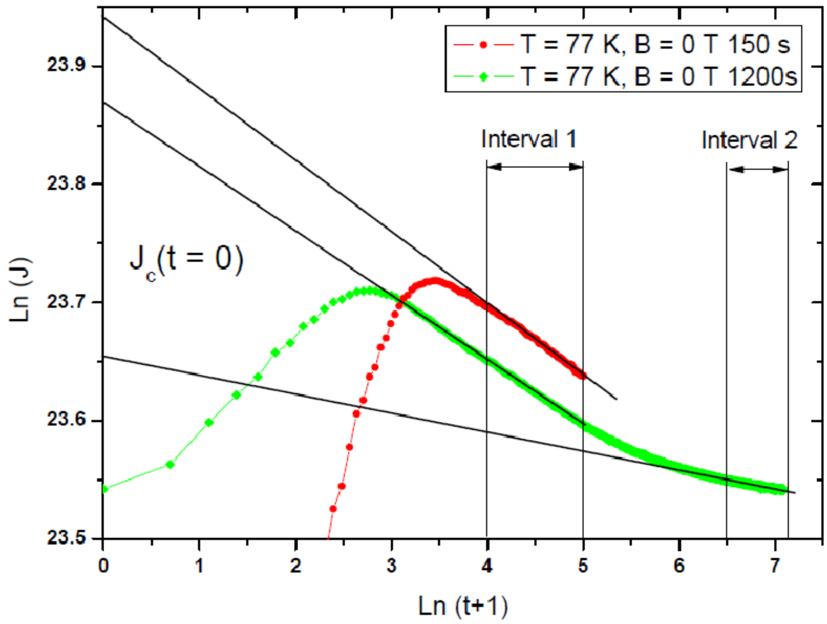

Figure 38. Time dependence of the critical current density J of the coated conductor as determined from the magnetization measurement and by applying the Bean model. The relaxation rate s is given by the slope of the ln J vs. ln time curve and is related to the pinning energy scale U_0 of the flux lines compared to the energy scale of the thermal fluctuations, k_BT by $s \sim k_BT/ U_0$.

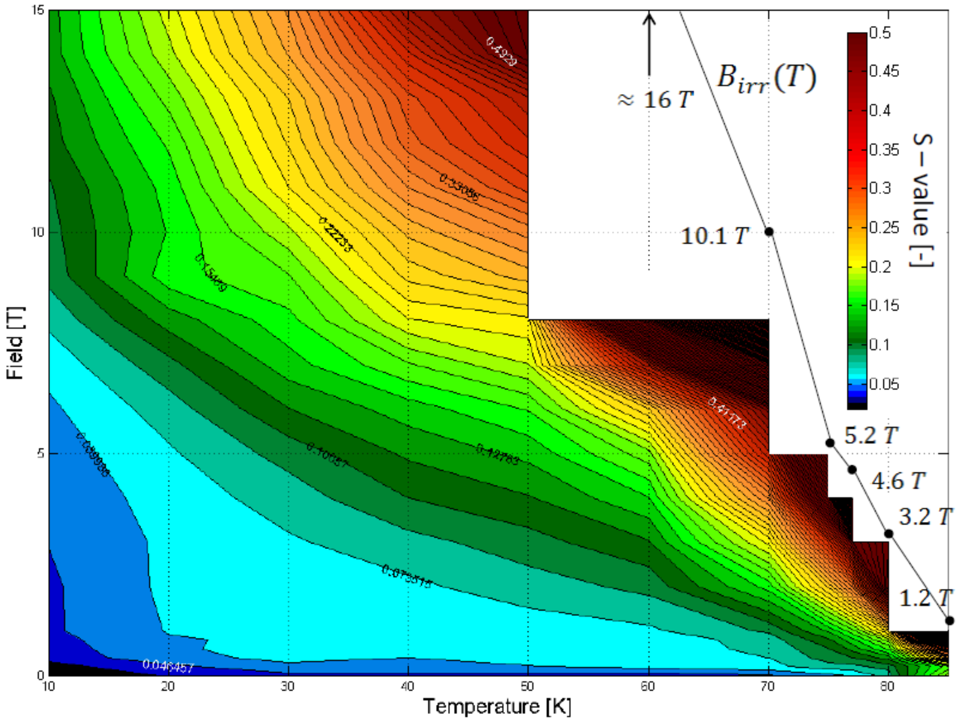

Figure 39. Dynamic phase diagram of coated conductor with I_C = 80 A (s.f. 77K) from Superpower illustrated by a color plot of the magnetic relaxation rate s = d lnJ / d ln t as function of applied field and operation temperature. The irreversibility line B_{irr} has been included in the phase diagram and shows where the critical current density vanishes. Thus fusion operation at T = 77 K will not be possible with the current tape, but subcooling of liquid nitrogen to T = 65 K will allow operation around B = 10 Tesla.

1. R. Bouchard, T. Lippmann, J. Neuefeind, H.-B. Neumann, H. F. Poulsen, U. Rütt, T. Schmidt, J. R. Schneider, J. Süssenbach and M. v. Zimmermann, *A Triple-Crystal Diffractometer for High Energy Synchrotron Radiation at the HASYLAB High Field Wiggler Beamline BW5*, Journal of Synchrotron Radiation, **5** (1998) 90-101

2. Cryogenic Limited, http://www.cryogenic.co.uk/products/measurement/vsm.asp

3. C. P. Bean, *Magnetization of High-Field Superconductors*, Rev. Mod. Phys. **36**, 31-39 (1964)

4. M. Nideröst, A. Suter, P. Visani and A. C. Mota, *Low-Field vortex dymamics over seven time decays in a* $Bi_2Sr_2CaCu_2O_{8+\delta}$ *single crystal for temperatures 13* $\leq T \leq$ *83 K*, Phys. Rev B. **53**, 9286 (1996).

5. A.B. Abrahamsen et. al., *Superconducting wind turbine generators*, Talk and paper at ISS2010, Tsukuba November 2010.

4 Risø contribution to EFDA-TIMES

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Within the Socio-Economic Research on Fusion (SERF) programme EFDA and the Associations are developing a multi-region global long-term energy modelling framework. The EFDA-TIMES model is a global model divided into 15 regions with the time horizon year 2100. This structure is similar to other global models, which are developed for the International Energy Agency (IEA) and the US Department of Energy. In these models the energy system is divided into the following main sectors: Upstream, Electricity, Industry, Residential, and Transport. Fusion technology is modelled in the Electricity sector in competition with renewables and electricity generating technologies based on fossil fuels or nuclear fission.

The technologies are organised into a network of energy flows linking demand and supply. Forecasts of energy demands in the various sectors come from global economic models. The energy system in EFDA is optimised by minimising total system costs subject to constraints reflecting infrastructure, technology availability and policy objectives. Most important of the latter is significant reduction of CO_2 and other greenhouse gasses.

The main characteristics of fusion within this model are:

Unit size 1.5 GW, similar to fission units or 2-3 large coal units

Base-load units operating more than 8000 hours per year

Steam parameters 600-800 ºC, similar to advanced coal or combined cycle gas turbines

Suitable for large-scale combined heat and power (CHP) for urban district heating or industrial processes

Suitable for catalytic hydrogen generation

Available from 2050 onwards

The key parameter for fusion is the investment cost per unit of installed capacity. When investment costs are high fusion will enter into the electricity generation mix only in cases of strict CO_2 constraints. Technology learning is likely to lead to lower costs, which may increase the share of fusion by the end of the century, given the assumptions on costs and availability of competing technologies.

1. Grohnheit, P.E., Using the IEA ETSAP modelling tools for Denmark, Risø-R-1656, Risø DTU, December 2008.
2. Grohnheit, P.E., Fusion in the energy system, Presented at: Meeting at European Environment Agency. Copenhagen (DK), 10 Nov. 2009

5 Industry awareness activities towards ITER

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Following the ITER site decision on June 28th 2005, Risø DTU was the main driver in the launch of activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER as described in some detail in [1]. This effort originally initiated in 2005 was further developed in 2006-2009. The main activity was the successful application for funds to increase the level of activity (more below).

To give a short overview the primary entry gate to the initiative for Danish companies is a website http://iter.risoe.dk. The website contains information on the coming tasks at ITER, background information, news and announcements of workshops etc., links to relevant international websites, description of experiences of other Danish companies, and an online database, where approximately 20 companies present their fusion relevant competences and their interests in ITER tasks. The database includes a number of significant players among Danish industries. It was the original intension that the webpage should also be used to advertise tender actions from ITER and F4E. However, until now it has been found to be more efficient to send out email alerts to the companies. This is done via a mailing list of more than 50 company contact persons. This has been the most important way of distributing news and advertising tender actions. The volume of the list has been steady over the last year with a few additions.

A group of companies and research institutes has formed an informal, non-exclusive network (further described in [1]): the Danish ITER Industrial Network. However, the activity level has been very low as there is a clear need for a driver on such long term initiatives. Furthermore, companies and other research institutes have a wish for support of the extensive preparations for ITER tasks. Risø DTU has competences to fulfil these needs, but the earmarked resources for the initiative in 2009 have been insufficient for the desired volume of the activities at Risø DTU.

In 2009, Risø DTU successfully applied for funds from the national Council for Technology and Innovation in collaboration with FORCE Technology and Teknologisk Institut (TI) (both are non-profit technology service institutes) and a number of companies. The partners were also behind the rejected application in 2008 for funds for a 4-year *innovationsnetværk* (network of innovation). In the meantime, significant effort was put by Risø DTU into developing a new setup. The result was a project called the Big Science Secretariat (BSS), which has a volume in excess of 7 million DKK with public support of 3.6 million DKK over a project period from April 2010 to October 2012. The project has participation by 12 companies with sizes in the range 5 to 15.000 employees. The application was supported by the Confederation of Danish Industry and several collaboration partners. Recently, the new minister of science has publicly expressed her support for the BSS project.

When BSS is fully deployed in October 2010 a full time employee will staff the secretariat. In addition, a number of experts in Risø DTU, FORCE, and TI will be connected to BSS, in order to assist Danish companies in their need for expert advice in the preparation phase. The aim of the initiative is two-fold: to increase the awareness of companies on the potential for participation in the construction phase of big science projects, and to assist companies in the required competence and network building phase prior to being able to bid for contracts on ITER, ESS, XFEL, ESO etc. BSS will see to connect to the Danish ILOs of the different organisations.

The Danish representative of the F4E-ILO network is still Søren B. Korsholm of Association Euratom – Risø DTU. The network now comprises 18 ILOs.

1. Association Euratom - Risø National Laboratory, Technical University of Denmark, Annual Progress Report 2006.

6 Public information in Denmark

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The public information activities in the Danish fusion association comprise a broad range of activities from press contact and assisting students to talks about fusion at different venues. A major part of the activities are the further development and the performances of the Fusion and Plasma Roadshow, described below in Section 6.1.

For brevity the activities are put in list form below

- More than a dozen popular lectures on fusion energy – mainly the roadshow – at high schools and at public science events.
- Presentation of fusion energy and fusion energy in the future energy system for the energy experts of the European Environmental Agency (EEA) by S.B Korsholm and P.E. Grohnheit.
- Web-TV interview on fusion in the context of the Youth Climate Summit before COP15.
- Assisting students from primary and high school in fusion oriented projects
- Collaboration with the new Science Talent Center at Sorø Akademi – teaching in fusion energy for high school student (talents) and teachers.
- Contact to journalists (web, newspapers, radio and TV) on fusion and ITER related news – in particular one feature article on fusion energy in Berlingske has been acknowledged widely in the Ministry of Science
- Continued participation in the *Scientarium* - the Panel of Experts of Ingeniøren – Engineering Weekly News Magazine

The EFDA Fusion Educational Poster was translated and printed in 2007 and an application for funds to be able to distribute the poster to all high schools in Denmark was submitted and approved. During 2009 181 out of 182 high schools in Denmark requested to receive between 1 and 4 posters pr. school. This project was funded and concluded in 2009.

Generally, regarding the Public Information effort, it is the impression that the interest is continually rising on the issue of fusion energy – not the least among the high school students.

6.1 The Danish fusion and plasma road show

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As part of the ongoing public information activities, the Danish Fusion and Plasma Road Show have been created by members of Association Euratom-Risø National Laboratory, Technical University of Denmark, DTU. The show was initiated in 2007 having the Dutch Fusion Road Show from FOM-Institute for Plasma Physics Rijnhuizen as inspiration. The show was funded for three years (2007-2009) by the Danish Research Council for Nature and the Universe under the Ministry for Science, Technology and Innovation – by a total of approx. 40,000 Euro.

The target audience of the Fusion and Plasma Road Show is primarily high school students, but has also been shown for a broader audience in public venues e.g. libraries. The show is participating in the Danish National Science Festival (September 2009) and in the National Day of Science (April 2009).

The objective of the show is to inform students and the general public about present fusion energy and plasma research and in that way give them an insight and hopefully an interest in science and its uses. In particular we hope that the students get inspired by the physics and see that fusion energy research is an exciting field with many possibilities. Another important objective is to inform about the use of fusion as a source of energy, and in that way clarify the benefits and challenges of fusion power.

The show is a combination of a regular slide based presentation and a number of small experiments that demonstrate or is related to a topic described in the presentation. The experiments are intended to surprise and excite people and also work as intermezzos in the talk. This is intended to help keep people focused on the topics. In the presentation a great effort is put in simplifying the advanced topics, and it is intended to bring the involved phenomena close to people's experiences from everyday life. This is done e.g. by converting enormous numbers in strange units into meaningful sizes, and also by asking questions or giving small exercises to the audience. The show has its own website: http://roadshow.risoe.dk, where descriptions of the experiments can be found.

In the course of the road show the following experiments are conducted

- An exercise bike connected to a generator and an inverter to be able to supply household appliances with power produced by the bike (New in 2009). This is a very popular experiment, where volunteers in the audience can get a feel for how much we should work to cover our consumption.
- Jacob's Ladder: Plasma created by 10.000 V between two copper wires
- Plasma in a microwave oven: Example of a RF generated plasma
- A ball on a rotating disc/turntable: Ball will move like a charged particle in EM-field
- Smoke rings: Example of the torus shape
- Electromagnet and compasses: Example of electricity generating a magnetic field
- Eddy currents in a copper plate with a strong magnet: Example of the connection between temperature and conductivity
- Superconductor – levitated magnet above superconductor
- Plasma ball lamp

Additional experiments are being developed.

In 2009 the roadshow has been performed thirteen times in Denmark in its regular form. Five of these were at high schools all over Denmark during the national Danish Science Festival in September 2009. At the National Day of Science in April 2009 two road shows were performed for school children, while the road show also participated in two four hour events in Frederiksberg (Copenhagen) and in Roskilde with roadshow presentations and an interactive booth. On top of this the road show was presented at the

Roskilde Music Festival, twice at Sorø Akademi for high school student talents and teachers, and at an international school conference.

The funding for the roadshow has stopped by the end of 2009. Unfortunately, the rules have been changed and it is currently not possible to apply for funds to this purpose. The roadshow is quite popular, and we have a waiting list of several high schools who wants to book the show. We are trying to find ways to fund the roadshow in the future.

Risø DTU is the National Laboratory for Sustainable Energy. Our research focuses on development of energy technologies and systems with minimal effect on climate, and contributes to innovation, education and policy. Risø has large experimental facilities and interdisciplinary research environments, and includes the national centre for nuclear technologies.

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